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An Experimental Study of a Novel Integrated Desiccant Air Conditioning System for Building Applications

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Abstract

To date, the application of liquid desiccant air conditioning systems in built environment applications, particularly small scale, has been limited. This is primarily due to large system size and complexity, issues of desiccant solution leakage and carry-over and equipment corrosion. As a result, a novel integrated desiccant air conditioning system (IDCS) has been developed. The system combines the regenerator, dehumidifier and evaporative inter-cooler into a single membrane based heat and mass exchanger. This paper presents an evaluation, based on experimental data, of the novel IDCS operating with a potassium formate ($CHKO_2$) desiccant working fluid. A range of tests have been completed to characterise the performance of the dehumidifier, regenerator and complete IDCS. Cooling output in the range of 570 to 1362W and dehumidifier effectiveness in the range of 30 to 47% are presented. An issue encountered has been an imbalance between moisture removal rate in the dehumidifier and moisture addition rate in the regenerator. As a result, an adjusted thermal COP ($COP_{th,adj}$) value has been calculated. $COP_{th,adj}$ values of 1.26 have been achieved with an average of 0.72. Electrical COP (COP_{el}) values of 3.67 have been achieved with an average of 2.5.

The work demonstrates that the novel IDCS concept is viable and has provided progress to the field of liquid desiccant air conditioning technology for building applications. Further work is required in order to address the main issue of mass imbalance between the dehumidifier and regenerator.

Keywords: Liquid desiccant, air conditioning, integrated design, building application, potassium formate.

1 Introduction

Buildings use significant quantities of energy, and thus they are a great contributor to CO_2 emissions. Heating, ventilation and air conditioning (HVAC) systems are a major source of this energy use in buildings, accounting for around 50% of total supplied energy [1]. Air conditioning is a major function within HVAC systems, and is widely used in a range of buildings such as homes, schools, supermarkets and sport centres. Although air conditioning has become a part of people's life needs in many Middle East, Far East, American and Southern European regions, it has more recently received growing use in Northern European countries, such as the UK, Denmark and Germany. This is due to more frequent warm spells, improved building insulation / air tightness and the use of in-house heat generating appliances [2].

Currently, the air conditioning market is dominated by vapour compression systems (VCS) because they have good stability in performance, low cost, long life and a reasonable electrical COP (COP_{el}) of between 2 – 4 [3]. However, VCS make use of harmful refrigerants such as R-22, R-410A, R-134A, materials with high global warming potential [4], and use significant quantities of electrical energy to drive the compressor. Owing to the fact that the most common form of electrical generation in the majority of counties is from the combustion of fossil fuels, VCS can be viewed as neither a sustainable nor efficient air conditioning option [5]. It is thus apparent, with an already high and continually growing global demand for air conditioning there is a need for alternative options that do not rely so heavily on harmful working fluids and fossil fuel derived electrical energy.

1.1 Alternative air conditioning technologies

There are a variety of alternative air conditioning systems; foremost amongst these are the sorption technologies, which reduce the requirement of electrical energy, but in place of this, increase the demand for thermal energy to operate. This thermal energy can be sourced from waste (process), solar, fuel cell etc. Thus, the associated CO_2 emissions in waste heat driven cooling cycles will be lower than an equivalent VCS, primarily due to a reduction in electrical requirement and the utilisation of waste/renewable heat for a useful process.

Closed cycle vapour absorption systems (VAS) replace the electrical driven compressor found in a VCS with a heat driven absorber and generator, these act in combination as a thermal compressor. VAS have a relatively low thermal COP (COP_{th}), in the range of 0.5

in single effect cycles up to 1.2 in double effect cycles [3, 6], which results in the intensive use of thermal energy. Furthermore, due to pressurised operation, the need for high temperature waste heat, expensive and corrosive chemical solutions, e.g., LiCl, LiBr, $CaCl_2$, VAS are relatively large and complex, and this has limited their attraction to many users [7] and to applications greater than 10kW [8]. Thus, a VAS cannot be viewed as a viable option, particularly for smaller (domestic) building applications.

An alternative to closed cycle vapour absorption is open cycle vapour absorption; also known as desiccant air conditioning. Desiccant air conditioning utilises the capability of desiccant materials to remove moisture from an air stream by the natural sorption process. Desiccant systems operate at atmospheric pressure and can either be solid (adsorption) or liquid (absorption). Both types have their advantages and disadvantages. Liquid desiccants have lower regeneration temperatures, greater dehumidification capacity and a lower air side pressure drop. Solid desiccants systems are compact, simple, less subject to desiccant carryover and corrosion [9]. In this paper a liquid desiccant system is presented.

A liquid desiccant air conditioning system consists of three main components: (1) dehumidifier (2) regenerator / regeneration heat source, and (3) an optional sensible cooling device. The role of the dehumidifier is to reduce the moisture content and temperature of supply air to provide a comfortable building environment for occupants. As moisture is absorbed by the liquid desiccant solution it becomes dilute and its ability to absorb moisture is reduced. In order to re-use the desiccant solution, a regenerator is used to evaporate off the moisture gained, thus increasing its concentration. The desiccant solution needs to be cooled prior to it being re-used in the dehumidifier. This is to enhance the dehumidification capacity of the solution and/or provide air sensible cooling. The solution / air sensible cooling process is most commonly achieved through evaporative means and can be a separate or con-current process to dehumidification.

The most commonly used liquid desiccant solutions used in air conditioning applications are known as halide salts, these include, Lithium Chloride (LiCl), Lithium Bromide (LiBr) and Calcium Chloride ($CaCl_2$). Advantages of these materials are they are there strong desiccants. LiBr and LiCl can dry air to a relative humidity of 6% and 11% respectively [10]. However the halide salts are extremely corrosive and cause significant damage to air conditioning equipment (heat exchangers, pipes etc.). Titanium is one of the few materials that can be used, however it is very expensive. In response to the shortcomings of the halide salts, other options have been explored. Salts of weak organic acids such as potassium formate ($CHKO_2$) or sodium formate (HCOONa) have been used [11]. These solutions have low toxicity and viscosity, are neither corrosive nor volatile, and they can, at the correct concentrations achieve sufficient dehumidification for comfort air conditioning in building applications. The concentration of $CHKO_2$ for air conditioning applications needs to be greater than that of the halide salts. For instance $CHKO_2$ at a 50% solution mass concentration is equivalent to the dehumidification potential of LiCl at a 27% solution mass concentration. Although it is a weaker desiccant than the halide salts, $CHKO_2$ ability to dehumidify air below 30% relative humidity and its favourable physical characteristics makes it an attractive option for building air conditioning applications [10].

A recent study of a liquid desiccant enhanced evaporative air conditioning system demonstrated a 30 – 90 % reduction in energy demand compared to an equivalent VCS [12]. Desiccant systems are currently competing in applications with large latent loads such as supermarkets and where high humidity may cause damage to property such as storage areas [11]. Although extensive work has been carried out on liquid desiccant air conditioning [13-17], system complexity and large geometrical size has severely limited their wider application and outweighed the significant energy savings they can achieve [9]. There is therefore a great need for simpler, more compact systems, particularly for building applications where space is often limited. Another major issue reported with liquid desiccant air conditioning systems is carry-over of the liquid desiccant solution into the supply airstream. This presents a health hazard to occupants and a corrosion risk for air conditioning plant and building. Liquid desiccant carry-over may be eliminated with the introduction of a semi permeable micro-porous membrane which allows the diffusion of water vapour but prevents the liquid desiccant solution migrating across it [18].

In response to these operational issues, a novel IDCS has been developed with the aim of permitting effective integration of liquid desiccant air conditioning in building applications. The novel IDCS has three design characteristics that aim to address the issues of system size and complexity, desiccant solution leakage and carry-over and equipment corrosion.

(1) A novel stack design integrates the regenerator, dehumidifier and evaporative inter-cooler into a single heat and mass exchanger (HMX), making the whole system more compact and less prone to leakage. The IDCS has less piping, heat exchangers and pumps compared to an equivalent conventional 'separate' system.

(2) The use of a semi-permeable micro porous membrane in the dehumidifier and regenerator HMX cores to prevent desiccant entrainment into the supply / working airstreams.

(3) Employment of an environmentally friendly, non-corrosive and low cost $CHKO_2$ desiccant solution.

This paper presents an evaluation, based on experimental data, of the novel IDCS operating with a $CHKO_2$ desiccant working fluid. No previous work has been found in the literature regarding an integrated design of this type. The work presented provides progress to the field of liquid desiccant air conditioning technology for building applications.

2 Experimental set-up

As previously stated, space, complexity and leakage is often cited as a significant barrier to the wider use of liquid desiccant air conditioning in buildings. As a result, an efficient and compact liquid desiccant system has been designed and built. The regenerator (R/C), dehumidifier (D/C) and evaporative inter-cooler (E/C) are combined into one single HMX core. The membrane HMX runs the entire length of the unit, but is subdivided into three different airflows, and two different fluid flows; desiccant and water. Thermal input to the regenerator is achieved through the heating of the inlet airstream in a liquid to air heat exchanger. Figure 1 shows a schematic of the integrated unit design concept. This design significantly reduces the number of heat exchangers, pipes and ducting often seen in liquid desiccant air conditioning systems, therefore reducing its total footprint.

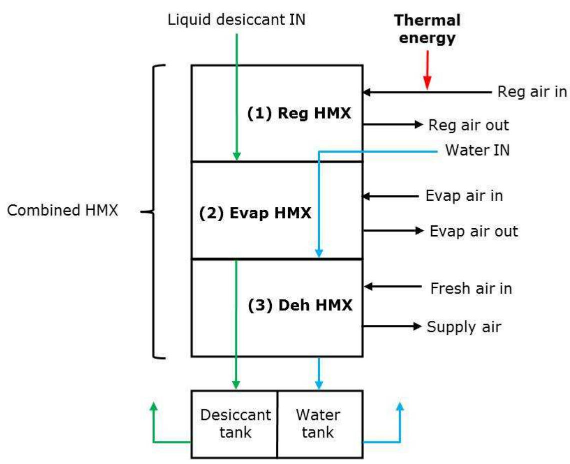

Figure 1 The novel IDCS concept

The novel IDCS design has three distinct advantages:

1. More compact form, essential for buildings applications
2. Reduced risk of desiccant leakage
3. Prevention of desiccant carry-over into supply / working air streams

Figure 2 provides a labelled schematic of the IDCS laboratory set-up including instrumentation and controls. A hot water cylinder is used as the regenerator thermal input.

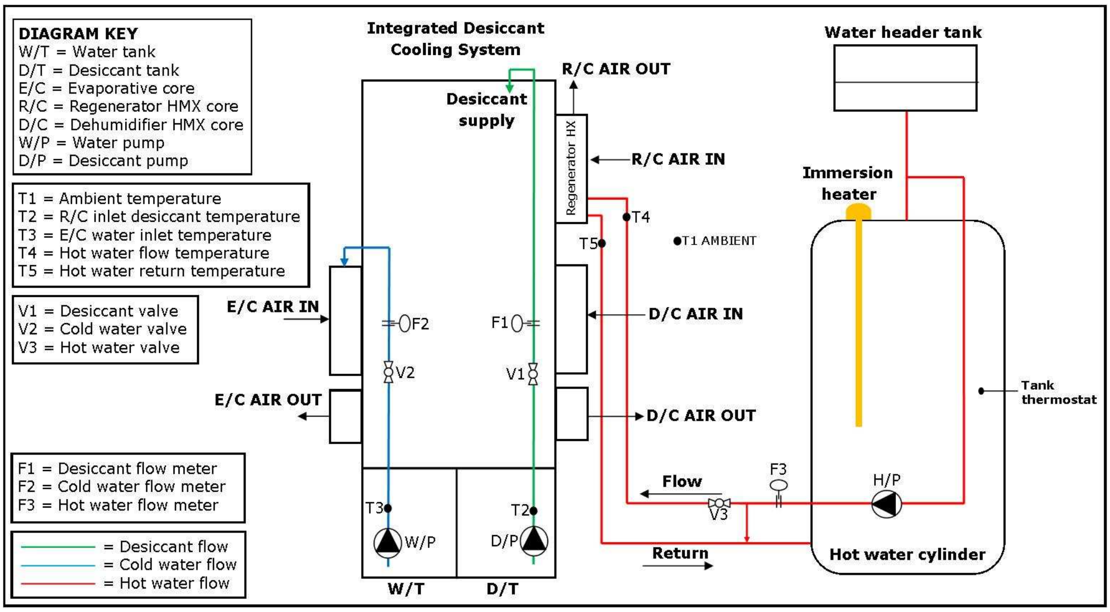

Figure 2 System schematic of the IDCS laboratory set-up

The IDCS HMX core consist of 26 channels that allow air and desiccant solution / water to flow in a cross flow manner (air through the core, desiccant / water downwards through the core), separated by a semi permeable micro-porous membrane. The solution channels consist of a polyethylene sheet, with membranes attached on either side. The gap between the two solution channels provides the space for the air to flow. The membrane allows the diffusion of water vapour, but prevents liquid desiccant solution migrating across it, thus overcoming the issue of liquid desiccant entrainment in the air stream. The regenerator core is 310mm in height, 420mm in width and has a depth of 240mm, with 26 air channels. The dehumidifier and evaporative inter-cooler core is 695mm in height, 420mm in width and has a depth of 240mm, with 26 air channels. The entire HMX core is contained in an aluminium box. The membrane HMX core sits on top of a 20 litre stainless steel split desiccant (D/T) and water tank (W/T). Weak desiccant solution is pumped, using a 15W single phase centrifugal magnetically driven pump (0-10L.min^{-1}), from the desiccant tank to the top of the unit where the regenerator is located. Here the desiccant is supplied through a spray nozzle, and flows in a downward direction due to gravity, contained within the membrane. Thermal energy is supplied to the regenerator by heating the regenerator airstream prior to it entering the regenerator HMX using a liquid to air heat exchanger. Heating of the airstream lowers the air side vapour pressure and thus drives mass transfer from the desiccant solution. Direct solution heating is not used due to the integrated design. The regenerator airstream is supplied to the unit via a 500m^3.hr^{-1} (nominal) 240V AC axial fan. The experimental work presented uses a vented 120 litre hot water cylinder with a 3kW electrical immersion heater as the regenerator heat source. However, the electrical immersion heater could be replaced with any heat source that can provide hot water at the desired temperature and flow rate i.e. waste, solar. A Wilo-Smart A-rated 230V AC pump has been employed to circulate the hot water in the heating circuit. A Honeywell L641A cylinder thermostat has been used to maintain the flow temperature from the tank at a constant temperature. The heated regenerator air stream then passes across the desiccant soaked membrane causing the dilute desiccant solution to be re-concentrated due to the removal of water by vaporisation into the regenerator air stream. The liquid desiccant leaves the regenerator as concentrated (strong) solution. The structure of the regenerator core is shown in Figure 3a and a photograph in Figure 3b. One side of the regenerator exchanger is blanked off. This is because in the regeneration process only one airstream is required, that to regenerate the desiccant solution. However, in the lower section of the IDCS there are two air processes, evaporative cooling and dehumidification, and so two air channels are required, as shown in Figure 4a.

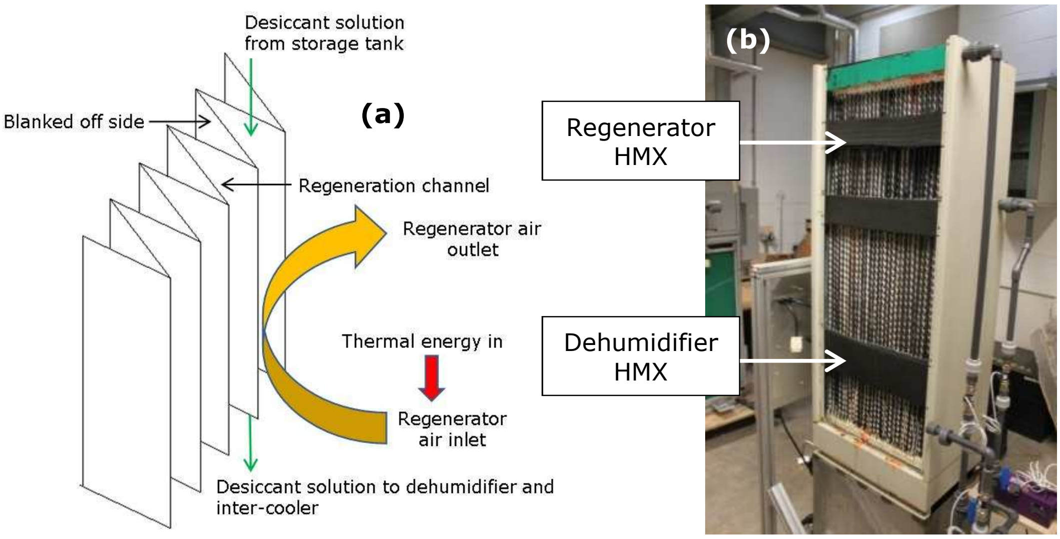

Figure 3 (a) Regenerator core operating concept, and (b) the regenerator HMX

After the regeneration process, the desiccant solution flows downwards due to gravity through the desiccant evaporative inter-cooler and dehumidifier. Here two processes occur simultaneously, (1) an evaporative cooling process creates a sensible cooling effect, which is transferred across the HMX wall to cool the desiccant solution and supply air stream, and (2) the supply air stream is dehumidified and cooled. The structure of the evaporative inter-cooler and dehumidifier core is shown in Figure 4a and a photograph in Figure 3b and Figure 4b. The evaporative cooling process is not only advantageous for the lowering of the supply air temperature; it also removes the latent heat of condensation produced during the dehumidification process and creates a lower vapour pressure in the desiccant solution and thus a greater dehumidification potential.

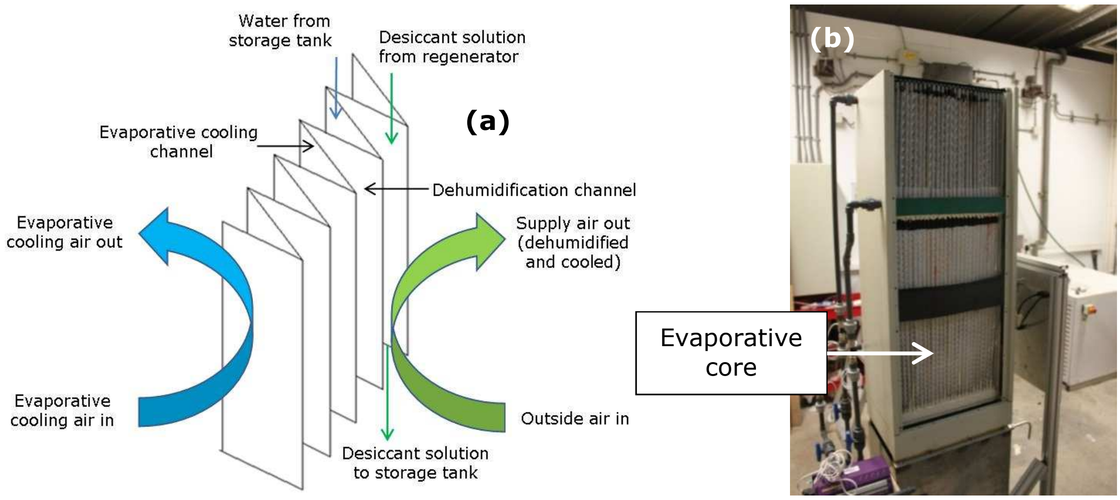

Figure 4 (a) Desiccant evaporative inter-cooler and dehumidifier operating concept, and (b) photograph of dehumidifier

Water is pumped using a 15W single phase centrifugal magnetically driven pump (0-10L.min^{-1}) from the water tank to the top of the evaporative core and is supplied through a spray nozzle. On the evaporative side of the HMX, water flows downwards due to gravity over the exchanger surface. The evaporative cooler airstream is supplied via a 500m^{3}.hr^{-1} (nominal) 240V AC axial fan. This air flows across the HMX in a cross-flow manner. This causes direct evaporative cooling and indirectly cools, through the exchanger wall, the liquid desiccant solution and dehumidifier supply air stream. Because the evaporative cooling and dehumidification processes are separated by the exchanger wall, sensible cooling is provided to the desiccant solution and supply airstream without moisture addition. On the dehumidifier side of the HMX, fresh air is supplied to the HMX core via a 500m^{3}.hr^{-1} (nominal) 240V AC axial fan. The fresh air flows in a cross flow manner across the desiccant soaked membrane. Due to the lower temperature (evaporatively cooled) and vapour pressure (regenerated) of the desiccant solution, the air is sensibly cooled and dehumidified. This air can then be supplied directly to the room, or can be passed through another evaporative cooling process to lower its temperature further. The warm and weak desiccant solution then flows back to the desiccant tank to begin the process again. The water used in the evaporative inter-cooler flows back to the separate tank.

Many of the liquid desiccant systems reported in the literature directly heat and cool the desiccant solution prior to the regeneration and dehumidification processes. However, in the IDCS because all desiccant flow is contained within one complete HMX the desiccant solution cannot be extracted for prior heating and cooling, thus heating of the regenerator air stream and the inclusion of an evaporative inter-cooler are required.

2.1 Instrumentation

All fans on the IDCS are equipped with Vent Axia infinitely variable fan speed controllers to enable control of the volumetric air flow through the HMX cores. The air inlet and outlet of the regenerator, dehumidifier and evaporative HMX cores are fitted with 125mm galvanised steel spiral tube ducting. The inlet and outlet air flows are instrumented with Vaisalia HMP110 humidity and temperature probes. The probes are mounted within the spiral tube ducting using special flanges. The humidity and temperature probes are factory calibrated. Air velocity through the regenerator, dehumidifier and evaporative inter-cooler cores are measured using an RS AM4204 hot wire anemometer at the air ducting outlets. The hot wire anemometer is factory calibrated. Air velocity measurements are recorded at five points across the air duct, and the average taken. The air velocity measurements are also validated against a TSI LCA501 rotating vane anemometer.

The desiccant and water pipes connecting the tank to the HMX core have been equipped with ball valves (V1 and V2 in Figure 2) so that the desiccant or water volumetric flow rate may be set to a desired value. A valve has also been placed on the hot water circuit (V3) to control the hot water flow to the regenerator. All water and desiccant solution flows have been instrumented with sheathed K-Type thermocouples (Nickel Chromium/Nickel Aluminium). Thermocouples have been placed at the inlet to the desiccant side (T2) and water side (T3) of the HMX core. Thermocouples have also been placed at the hot water inlet (T4) and outlet (T5) to the regenerator liquid to air heat exchanger.

The desiccant solution and water volumetric flow is measured using a 0.2 to 2L.min^{-1} Parker Liquid Flow Indicator. These are placed on the pipe connecting the tank to the HMX core (F1 on desiccant side, and F2 on water side). The flow meters used are calibrated for water at 20°C according to density and viscosity. Thus, for the water flows used in the system, no correction is required. For the desiccant solution flow a correction factor is required to equate the volumetric flow shown on the flow meter to the actual desiccant flow. This correction correlation is shown in Equation 1 [19].

$$v_{sol} = v_{\mathrm{w}} \sqrt{\frac{(m_{\mathrm{float}} - V'_{\mathrm{float}}\rho_{\mathrm{sol}})\rho_{\mathrm{w}}}{(m_{\mathrm{float}} - V'_{\mathrm{float}}\rho_{\mathrm{w}})\rho_{\mathrm{sol}}}} \quad \mathbf{1}$$

v_{sol} and v_{w} is the volumetric flow in L.min^{-1} of the desiccant solution and water respectively. For the flow meters used the float weight, $m_{\mathrm{float}} = 2.1 \times 10^{-3} kg$ and the float volume $V'_{\mathrm{float}} = 0.25 \times 10^{-6} m^3$.

The hot water cylinder is equipped with an RS 1–15L.min^{-1} piston flow meter (F3), designed for flow temperatures of up to 60°C. All desiccant solution and water flows on the IDCS are equipped with 20mm PVC-U plastic pipe, with plastic fittings. The hot water cylinder is piped with insulated 22mm copper pipe and copper fittings. Flexible PVC hot water hose is used to connect the hot water cylinder to the regenerator liquid to air heat exchanger.

For the accurate evaluation of the desiccant system, the working concentration of the desiccant solution needs to be determined. Using a correlation based on the work of Melinder [20] the desiccant solution concentration is determined from the solution density (ρ_{sol}) and temperature (T_{sol}). In the experimental work the density of the desiccant solution is measured using a differential pressure density meter with temperature compensation. The meter has been designed to work in the density range of the $CHKO_2$ solution (1400 to 1550kg.m^{-3}) and has been calibrated with water. The measurement prongs of the differential pressure density meter are placed in the desiccant solution tank and held until a steady-state reading is achieved. The temperature of the solution is measured using the K-Type thermocouple at the tank outlet. The concentration is then calculated using the correlation presented in Equation 2.

$$X_{sol} = -253.147703 + 0.0443853996\, T_{sol} + 0.000163666247\, {T_{sol}}^2 + 0.331709855\, \rho_{sol} - 0.0000793702671\, {\rho_{sol}}^2 \quad (2)$$

The electrical consumption of fans and pumps are measured using a Brennenstuhl PM230 electricity monitor. This is essential for the COP_{el} calculations. At full load the desiccant system parasitic electrical load is measured at 400W. A DataTaker DT500 datalogger is used to record the data from the sensors every ten seconds.

Further details of the measuring equipment used and their associated accuracy are listed in Table 1.

Table 1 Instrumentation equipment and associated accuracy

Measurement device	Measurement subject	Measurement range	Measurement accuracy
HMP110 relative humidity and temperature probe	Air relative humidity and temperature	0 to 90% RH 0 to 40°C	RH_a = ± 1.7% RH T_a = ± 0.2°C
RS AM4204 hot wire anemometer	Air velocity	0 to 20 m.s^{-1}	u_a = ± 5% of reading
K-Type thermocouple probe	Desiccant solution and water temperature	0 to 1100°C	T_{sol} / T_{water} = ± 2.2°C
Parker Liquid Flow Indicator	Desiccant solution and water volumetric flow	0.2 to 2L.min^{-1}	v_{sol} / v_{water} = ± 2% of reading
Desiccant solution density meter	Desiccant solution density	1400–1550 kg.m^{-3}	ρ_{sol} = ± 10 kg.m^{-3}
Brennenstuhl PM230 electricity monitor	IDCS electrical power usage	Up to 16 Amps	W_{IDCS} = ± 3 % of reading

2.2 Uncertainty analysis

Uncertainty analysis provides a measure of the error associated with a calculated value. Using the propagation of error formula [21] the absolute uncertainty of a calculated value can be calculated. The maximum relative uncertainty values for the dehumidifier, regenerator and complete system performance studies are presented in their respective experimental results section. Absolute uncertainty values for six sample dehumidifier, regenerator and system performance studies are shown in Table 4 - Table 6 respectively. It has been identified that the largest source of error comes from the relative humidity measurement which is fundamental to all calculations. The K-Type thermocouples are also a large source or error and fundamental to the COP calculations.

2.3 Experimental method

The IDCS is installed at The University of Nottingham's Marmont Laboratory. This is to facilitate evaluation under varying environmental and operating conditions in controlled laboratory conditions. There are three main components to the laboratory experimental set-up shown in Figure 5: (1) the novel IDCS, (2) hot water cylinder and (3) environmental chamber. Table 2 provides IDCS air flow identification.

Figure 5 IDCS laboratory setup with labelled air flows

Table 2 IDCS air flow identification

Air flow ID	Air flow description	Air flow ID	Air flow description
A	Regenerator HMX inlet	D	Dehumidifier HMX outlet
B	Regenerator HMX outlet	E	Evaporative cooler inlet
C	Dehumidifier HMX inlet	F	Evaporative cooler outlet

The use of the environmental chamber facilitates: (a) a high level of control and provides consistent inlet air conditions to the IDCS throughout all tests, and (b) simulation of different climates other than the UK; specifically those that favour the use of liquid desiccant air conditioning i.e. high humidity. The environmental chamber can create air conditions from 0 to 40°C and 10 to 80% relative humidity. The dehumidifier (supply) air stream is connected to the environmental chamber by the way of a plenum box. However, the regenerator and evaporative inter-cooler air streams use the air from the laboratory environment. This is because the complete IDCS could not fit in the environmental chamber, and the air flow requirements of the entire IDCS were too high to duct all air flows from the chamber to the IDCS. The desiccant evaporative inter-cooler will perform better with laboratory (room) air as opposed to environment chamber (outside) air as it is drier and thus represents a greater evaporative potential. Similarly, the regenerator will perform better with lower humidity laboratory air because it possesses a lower vapour pressure. Therefore using laboratory (room) air for the evaporative and regeneration processes will improve system performance. All outlet air flows are to the laboratory environment.

At the beginning of a test, the temperature and relative humidity of the environmental chamber are set. Depending on the requirements it can take up to one hour to achieve stable and homogenous air conditions inside. The temperature and relative humidity shown on the chambers display panel is cross checked against the Vaisalia HMP110 humidity and temperature probe at the IDCS dehumidifier inlet and an RS 1365 handheld humidity-temperature meter within the chamber. Once the desired air conditions are achieved, and depending on the test variable under investigation, the IDCS operation is set accordingly and run at that condition.

For desiccant solution regeneration, a vented 120 litre hot water cylinder with a 3kW electrical immersion heater is used as the thermal input. Before the start of a test the hot water tank heater and circulation pump (H/P) are switched on. A by-pass loop is used to circulate the water around the tank until it reaches the desired temperature for the particular test. A control valve (V3) on the flow pipe is used to provide the desired hot water flow to the IDCS. The tank thermostat is set according to the required flow temperature. The flow temperature from the tank is checked at regular intervals.

The desiccant solution concentration in the tank is recorded at the start, middle and end of each separate test, and the result recorded. The air velocity is measured at each duct outlet and recorded at the beginning of each test, and the result recorded. Multiplication of the average air velocity by the air duct area provides the volumetric air flow through the HMX cores. The desiccant solution and water volumetric flows are measured at the start of a test, and the flow indictors checked periodically throughout a test. Depending on the test variable being investigated, tests last for 30-60 minutes or until steady-state outlet air conditions are achieved for extended periods (30 minutes or more). Data is recorded every ten seconds in this period. Only steady-state data is used in the performance evaluation. Testing of the dehumidifier and regenerator components are carried out con-currently. This is due to the operational nature of the combined IDCS. For each variable investigated there were a minimum of three individual tests conducted. The results presented are the average of each of these tests.

2.3.1 Performance evaluation metrics

The performance of the dehumidifier is evaluated on the basis of moisture removal rate, change in absolute humidity of air across the dehumidifier, latent heat transfer (dehumidifier) effectiveness and cooling output.

The dehumidifier moisture removal rate (MRR) in g.s^{-1} is shown in Equation 3.

$$\text{MRR} = \dot{m}_{a,deh}\left(\omega_{a,in,deh} - \omega_{a,out,deh}\right) \tag{3}$$

$\dot{m}_{a,deh}$ is the mass flow of rate air passing through the dehumidifier HMX core in kg.s^{-1}. $\omega_{a,in,deh}$ and $\omega_{a,out,deh}$ are the dehumidifier's respective inlet and outlet air absolute humidity in kg_{vapour}/kg_{dryair}.

The change in the absolute humidity (kg_{vapour}/kg_{dryair}) of air across the dehumidifier is shown in Equation 4.

$$\Delta\omega_{deh} = \omega_{a,in,deh} - \omega_{a,out,deh} \tag{4}$$

The latent heat transfer (dehumidifier) effectiveness, shown in Equation 5, is the ratio of actual moisture transferred to the maximum moisture transfer.

$$\eta_L = \frac{\omega_{a,in,deh} - \omega_{a,out,deh}}{\omega_{a,in,deh} - \omega_{eq,deh}} \tag{5}$$

ω_{eq} is the equivalent moisture content in kg_{vapour}/kg_{dryair} of the desiccant solution at the inlet condition, and is a function of its concentration and temperature as shown in Equation 6.

$$\omega_{eq} = 0.622\left(\frac{p_{sol}(X_{sol}, T_{sol})}{p_{atm} - p_{sol}(X_{sol}, T_{sol})}\right) \tag{6}$$

p_{sol} is the vapour pressure in Pa of the desiccant solution at a specified concentration and temperature. p_{atm} is atmospheric pressure and is equal to 101325Pa. X_{sol} is the desiccant solution mass concentration, determined using Equation 2. T_{sol} is the solution temperature in °C.

The dehumidifier cooling output in W is shown in Equation 7:

$$\dot{Q}_{cooling} = \dot{m}_{a,deh}\left(h_{a,in,deh} - h_{a,out,deh}\right) \quad \textbf{7}$$

$h_{a,in,deh}$ and $h_{a,out,deh}$ are the respective inlet and outlet specific enthalpies of the air entering and leaving the dehumidifier HMX core in J.kg^{-1}. Air enthalpy is a function of both temperature and absolute humidity. Therefore air cooling means lowering temperature and / or absolute humidity.

The performance of the regenerator is evaluated on the basis of: moisture addition rate and regenerator thermal input.

The regenerator moisture addition rate (MAR) in g.s^{-1} is shown in Equation 8.

$$\mathrm{MAR} = \dot{m}_{a,reg}\left(\omega_{a,out,reg} - \omega_{a,in,reg}\right) \quad \textbf{8}$$

$\dot{m}_{a,reg}$ is the mass flow rate of air passing through the regenerator HMX in kg.s^{-1}. $\omega_{a,out,reg}$ and $\omega_{a,in,reg}$ are the regenerator's respective inlet and outlet air absolute humidity in kg_{vapour}/kg_{dryair}.

The regenerator thermal input, $\dot{Q}_{reg}$ in W is determined using Equation 9.

$$\dot{Q}_{reg} = \dot{m}_{w,reg} c_{p,w,reg}\left(T_{w,\mathrm{flow}} - T_{w,\mathrm{return}}\right) \quad \textbf{9}$$

$\dot{m}_{w,reg}$ and $c_{p,w,reg}$ are the respective mass flow rate in kg.s^{-1} and specific heat capacity in J.kg^{-1}.K of the water in the regenerator heating circuit. $T_{w,flow}$ and $T_{w,return}$ are the respective heating circuit flow and return water temperatures in °C.

Overall IDCS performance is evaluated using COP_{th} and COP_{el}. These are defined in Equations 10 and 11 respectively.

$$\mathrm{COP}_{th} = \frac{\dot{Q}_{cooling}}{\dot{Q}_{reg}} \quad \mathbf{10}$$

$$\mathrm{COP}_{el} = \frac{\dot{Q}_{cooling}}{\dot{W}_{aux,des}} \quad \mathbf{11}$$

$\dot{W}_{aux,des}$ is the IDCS electrical requirement (fans and pumps). Depending on the test conditions this ranged from 370W – 400W. The thermophysical properties of the humid air are determined from in-built functions in Engineering Equation Solver. The thermophysical properties of the desiccant solution are determined from linear regression curve fits to published data [20, 22].

3 Results and analysis

This section presents the results and analysis from the dehumidifier, regenerator and complete IDCS experimental evaluation. Due to the combined nature of the IDCS the desiccant solution flow in the regenerator HMX has to equal that in the dehumidifier HMX. Due to the combined and integrated nature of the system measurement of the desiccant solution properties between the regenerator and dehumidifier is not possible. Unless otherwise varied, Table 3 provides the operating values used in the experimental evaluation of the dehumidifier, regenerator and complete IDCS.

Table 3 Operating values used in the evaluation of the IDCS

Variable	Dehumidifier	Inter-cooler	Regenerator
Desiccant /water flow (L.min^{-1})	1.5	1.5	1.5
Desiccant temperature (°C)	23 - 26	---	---
Water temperature (°C)	---	22 - 25	---
Solution mass concentration (-)	0.65 – 0.7	---	0.65 – 0.7
Volumetric air flow (m^3.hr^{-1})	243	269	243
Inlet air temperature (°C)	30	22–26	22–26
Inlet air relative humidity (%)	60	38-66	38-66

Throughout all tests a desiccant solution volumetric flow of 1.5L.min^{-1} was used. It was found through experimental evaluation that a volumetric flow above 1.5L.min^{-1} resulted in desiccant solution entrainment in the supply airstream, and below 1.5L.min^{-1} leads to insufficient wetting of the membrane surface.

3.1 IDCS dehumidifier component analysis

The role of the dehumidifier is to cool a supply air stream through the lowering of its enthalpy. Enthalpy reduction is achieved primarily through the removal of moisture from the air stream to a liquid desiccant solution. Depending on the desiccant solution temperature, a reduction in the supply air temperate may also occur. The IDCS dehumidifier component evaluation has assessed the impact of inlet air temperature, inlet air relative humidity and volumetric air flow on dehumidifier performance. Table 4 presents the results for six sample dehumidifier tests along with their associated absolute uncertainty.

3.1.1 IDCS dehumidifier inlet air condition effect

The IDCS dehumidifier performance has been evaluated over a 50-70% relative humidity range at a 30 and 35°C inlet air temperature. The data presented in Figure 6 shows that dehumidifier performance improves with increasing inlet air temperature and relative humidity. Figure 6a shows that over the investigated relative humidity range the moisture removal rate from the supply airstream increases from 0.1541 to 0.4395g.s^{-1} for the 30°C inlet air condition and 0.2354 to 0.4682g.s^{-1} for the 35°C inlet air condition. As the relative humidity and temperature of the inlet air increases, its vapour pressure increases, and thus a greater vapour pressure difference between the humid air and desiccant solution exists, driving greater mass transfer. Figure 6b shows that over the investigated relative humidity range the absolute humidity difference of the supply air stream increases, i.e. more dehumidification occurs, from 0.001988 to 0.005728kg$_{vapour}$/kg$_{dryair}$ for the 30°C inlet air condition, and from 0.003073 to 0.0062kg$_{vapour}$/kg$_{dryair}$ for the 35°C inlet air condition. Figure 6c shows that over the investigated relative humidity range the latent (dehumidifier) effectiveness increases from 29.91 to 38.39% for the 30°C inlet air condition, and from 32.32 to 46.78% for the 35°C inlet air condition. Figure 6d shows that over the investigated relative humidity range the cooling output from the dehumidifier increases as the inlet air relative humidity and temperature increases. The dehumidifier cooling ranges from 570W to 1084W at an inlet temperature of 30°C, and from 1059W to 1362W at an inlet temperature of 35°C. The increase in cooling output with air relative humidity and temperature is due to greater moisture removal rate and thus greater latent cooling, plus a greater temperature difference between the air and desiccant solution leading to increased sensible cooling.

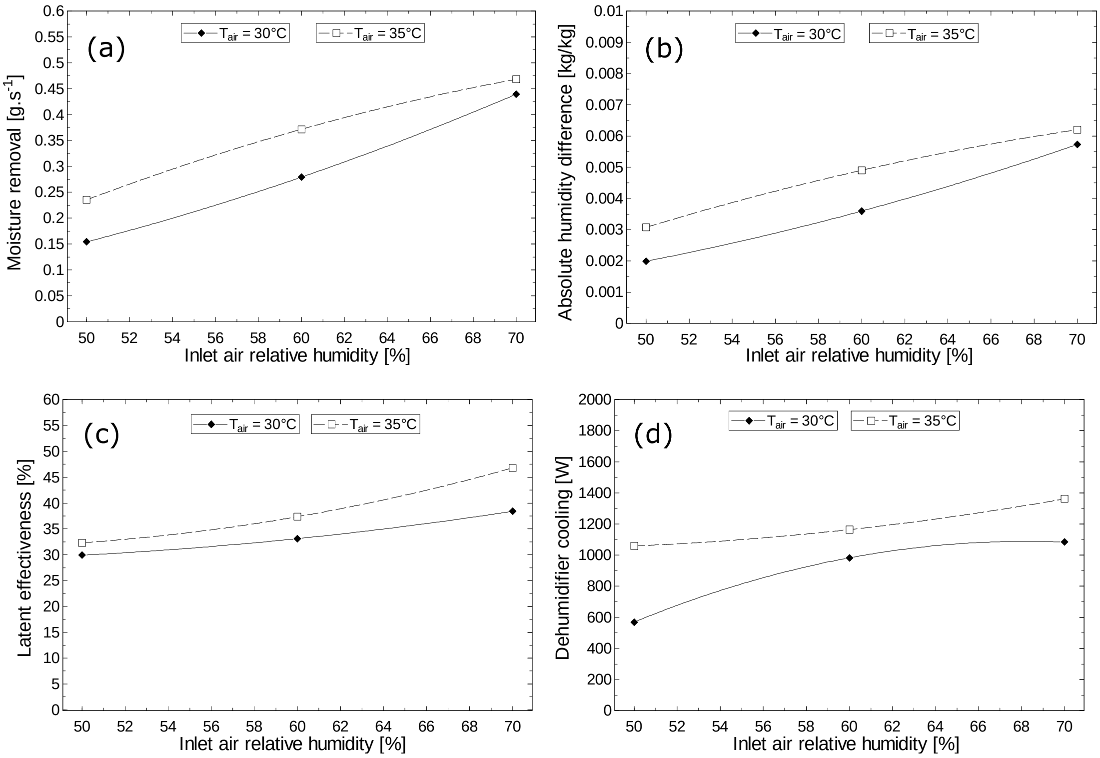

Figure 6 (a) to (d) IDCS dehumidifier performance with inlet air conditions

At the 30°C and 35°C inlet air condition, the average supply air temperatures across all relative humidity tests is 28.81°C and 31.97°C respectively. From Figure 6 it is evident that the IDCS dehumidifier performance improves with an increase in inlet air temperature and relative humidity. The system is therefore well suited to hotter, more humid climate such as Southeast Asia. However increased performance will result in a greater dilution of the desiccant solution. For building applications consideration needs to be given to whether the regenerator moisture addition rate achievable with the available thermal input can match the mass removal rate in the dehumidifier otherwise dilution of the desiccant solution over time will occur.

The IDCS evaporative inter-cooler is included to enhance performance by providing sensible cooling to the dehumidification process. The evaporative inter-cooler is operated on laboratory air. Figure 7 shows the relationship between the inlet air absolute humidity to the evaporative inter-cooler and the cooling it provides. The cooling output is determined based on the enthalpy difference of the inter-cooler's inlet and outlet air. At an inlet air condition of $0.007kg_{vapour}/kg_{dryair}$ around 800W of cooling is achieved, this reduces to around 400W at a $0.011kg_{vapour}/kg_{dryair}$ inlet air condition. At lower inlet air absolute humidity values, the evaporative cooler produces a greater cooling output due to the inlet air having a lower wet-bulb temperature and thus greater evaporative potential. As a result, in a building application it is recommended to operate the evaporative inter-cooler on drier room air, as opposed to fresh outside (humid) air.

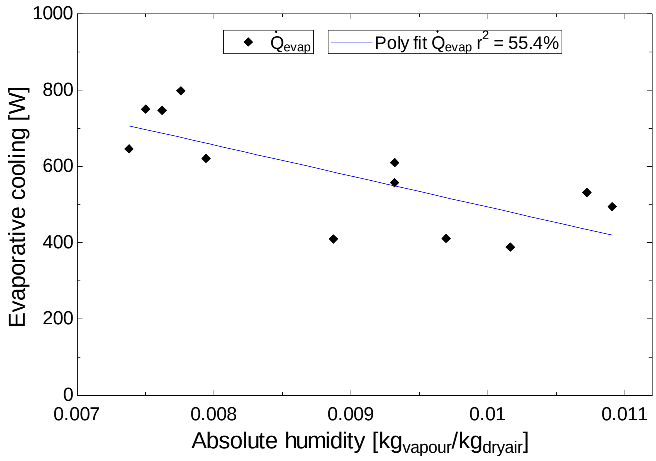

Figure 7 IDCS evaporative-inter cooler output with inlet air absolute humidity

3.1.2 IDCS dehumidifier volumetric air flow effect

Figure 8 shows the impact inlet air volumetric flow has on dehumidifier performance at a set inlet condition of 30°C and 60% relative humidity. Figure 8a shows the moisture removal rate increases with volumetric air flow, from $0.2058g.s^{-1}$ at $124m^3.hr^{-1}$ (fan setting 1) to a maximum of $0.2978g.s^{-1}$ at $243m^3.hr^{-1}$ (fan setting 3). There is little difference ($<0.0116g.s^{-1}$) between the moisture removal rate achieved between $217m^3.hr^{-1}$ (fan setting 2) and $243m^3.hr^{-1}$ (fan setting 3). Figure 8b shows that as the dehumidifier air volumetric flow increases the change in absolute humidity of the air across the dehumidifier reduces from $0.005146kg_{vapour}/kg_{dryair}$ at $124m^3.hr^{-1}$ to $0.003594kg_{vapour}/kg_{dryair}$ at $243m^3.hr^{-1}$. As volumetric air flow increases a greater mass of air is passed through the dehumidifier and thus the capacity of the dehumidifier to reduce the air absolute humidity reduces. This relationship is in conflict with the moisture removal rate shown in Figure 8a. This is because moisture removal rate is a function of air mass flow rate. Figure 8c shows that as the dehumidifier air volumetric flow increases the latent (dehumidifier) effectiveness reduces from 68.52% at $124m^3.hr^{-1}$ to 37.35% at $243m^3.hr^{-1}$. Figure 8d shows the dehumidifier cooling output increases as the volumetric air flow increases from a minimum of 613W at $124m^3.hr^{-1}$ to 1065W at $243m^3.hr^{-1}$. This is primarily due to a larger volume of air being conditioned.

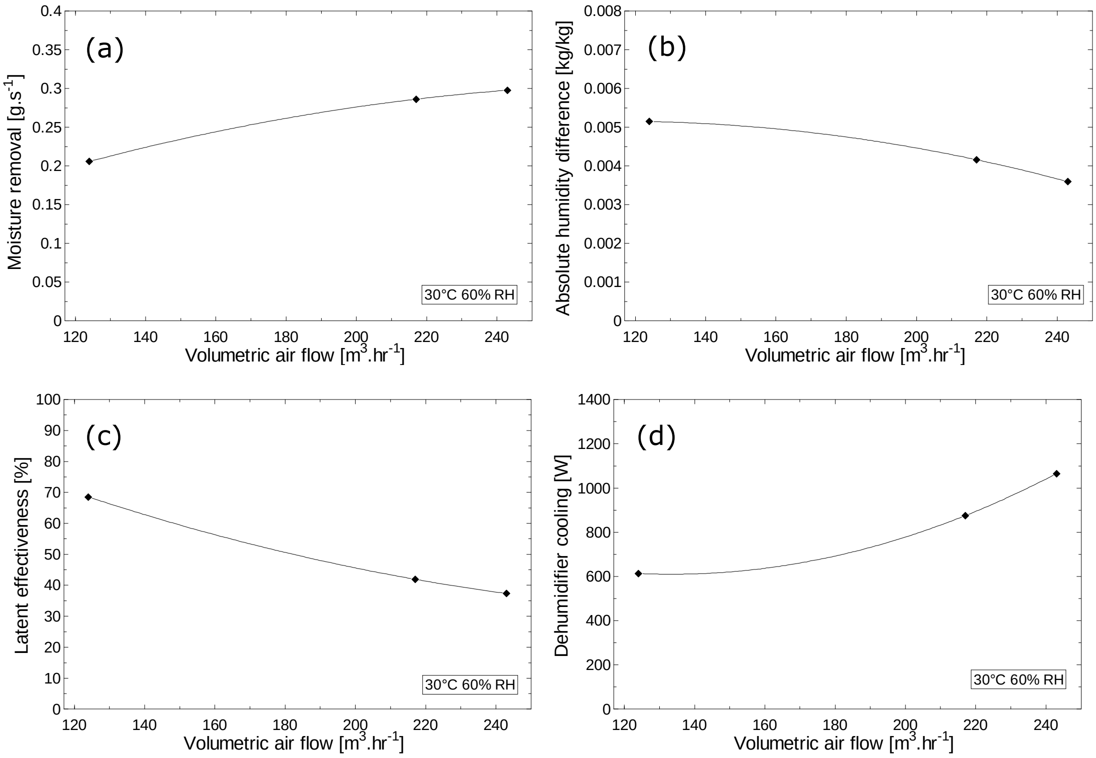

Figure 8 (a) to (d) IDCS dehumidifier performance with inlet air volumetric flow

The selection of an appropriate volumetric air flow in the dehumidifier is dependent upon the application and the desired supply air condition. Across all dehumidifier tests the maximum calculated relative uncertainties in the dehumidifier MRR, $\Delta\omega$, η_L and $\dot{Q}_{cooling}$ were ±15.98%, ±15.1%, ±12.47%, and ±15.04% respectively.

3.1.3 IDCS dehumidifier component analysis conclusions

Over the investigated environmental conditions the dehumidifier performs well with a $CHKO_2$ solution at a 0.65 - 0.7 solution mass concentration. Dehumidifier moisture removal rates and cooling output increase with inlet air temperature and relative humidity in the range of 0.1541 to 0.4682g.s^{-1} and 570W to 1362W respectively. The dehumidifier effectiveness values range from 30 - 47%, typical of a membrane based HMX. Volumetric air flow has little impact on moisture removal but a marked impact on absolute humidity difference across the dehumidifier, latent effectiveness and dehumidifier cooling output. The evaporative inter-cooler provides between 400 and 800W of cooling to the dehumidifier. The performance of the evaporative-inter cooler performance is strongly linked to the inlet air absolute humidity. Thus, in a building application it is beneficial to operate the evaporative inter-cooler on drier return room air.

3.2 IDCS regenerator component analysis

The aim of the regeneration process is to remove the water vapour gained by the desiccant solution during the dehumidification process. The moisture removal rate from the dehumidifier air stream to the desiccant solution should equal the moisture addition rate from the desiccant solution to the regeneration air stream and thus the complete system can run continuously. During regenerator evaluation a water flow temperature of 60°C and water volumetric flow in the heating circuit of $2L.min^{-1}$ was used. The IDCS regenerator component evaluation has assessed the impact of inlet air absolute humidity, volumetric air flow and volumetric water flow in the heating circuit on regenerator performance. Table 5 presents the results for six sample regenerator tests (same sample as dehumidifier), along with their associated absolute uncertainty.

Figure 9a shows the impact inlet air absolute humidity to the regenerator has on moisture addition rate. The inlet air temperature to the regenerator ranges from 22 - 26°C and the absolute humidity ranges from 0.00708 to $0.01197kg_{vapour}/kg_{dryair}$. The moisture addition rate ranges from a minimum of $0.07715g.s^{-1}$ to a maximum of $0.2229g.s^{-1}$. Mass transfer is driven by a vapour pressure difference between the desiccant solution and the regenerator airstream. As the absolute humidity of the regenerator inlet airstream increases so does its vapour pressure, resulting in a smaller moisture addition rate.

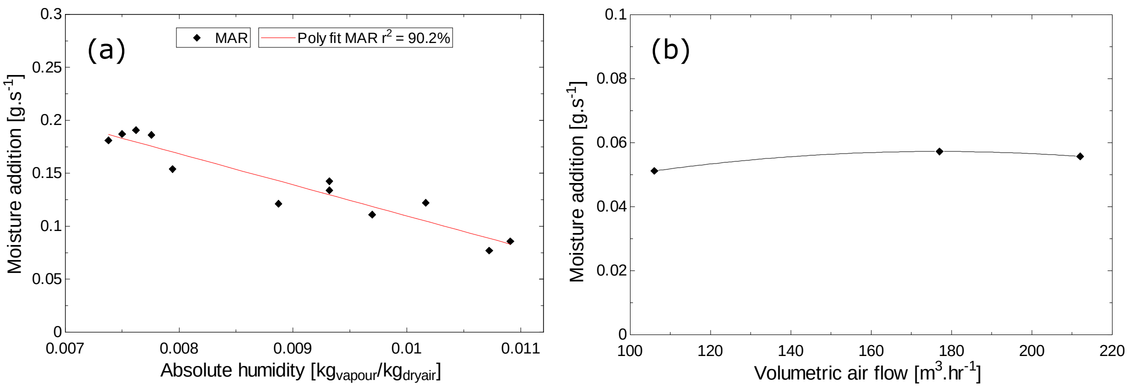

Figure 9 IDCS regenerator performance with (a) inlet air absolute humidity, and (b) volumetric air flow

Figure 9b shows the variation of moisture addition rate from the desiccant solution to the regenerator airstream as a function of regenerator volumetric air flow. The novel IDCS integrates three components; regenerator, dehumidifier and evaporative inter-cooler into one HMX core. As a result, the operation of each component has an impact on the others. During volumetric air flow evaluation, the regenerator was operated independently i.e. no dehumidifier or evaporative cooler and as a result the regenerator volumetric air flow shown in Figure 9b is lower than that observed during simultaneous dehumidifier and regenerator operation. The regenerator volumetric air flow rate is increased from $106m^3.hr^{-1}$ to $212m^3.hr^{-1}$. It is evident that the volumetric air flow has little impact on the moisture addition rate, with values ranging between 0.05118 to $0.05727g.s^{-1}$, an increase of $0.00609g.s^{-1}$.

Figure 10a shows the variation of the moisture addition rate in the regenerator with respect to the volumetric water flow in the regenerator hot water heating circuit over a 1.5 - $6.5L.min^{-1}$ range. It is evident that the volumetric flow of the water has a marginal impact on regenerator capacity, with the moisture addition rate ranging from $0.2363g.s^{-1}$ to $0.2619g.s^{-1}$, a difference of $0.0256g.s^{-1}$

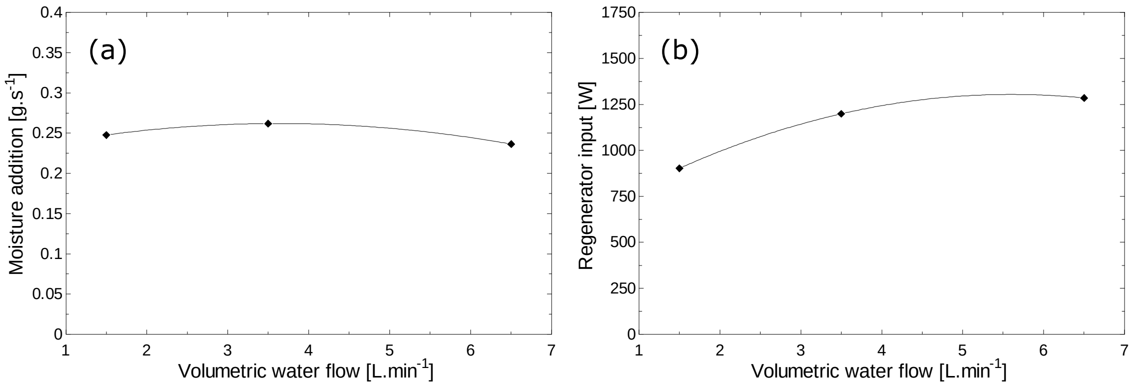

Figure 10 (a) to (b) IDCS regenerator performance with heat exchanger volumetric water flow

Figure 10b shows the regenerator thermal input as a function of volumetric water flow in the regenerator liquid to air heat exchanger. The volumetric water flow has a large impact on the thermal input to the system. At $1.5L.min^{-1}$ the thermal input is 903W at $6.5L.min^{-1}$ the thermal input is 1285W. As highlighted in Figure 10a the volumetric water flow has little impact on the moisture addition rate in the regenerator, it is therefore optimal to operate the IDCS at a $1.5L.min^{-1}$ volumetric water flow in the regenerator hot water circuit., having a lower regenerator thermal input but a similar moisture addition rate will assist in improving the COP_{th} of the IDCS. This is discussed in more detail in Section 3.3. Across all regenerator tests the maximum calculated relative uncertainty in the regenerator MAR was ±25.6%.

3.2.1 IDCS regenerator component analysis conclusions

Regeneration capacity increases with a lower inlet air absolute humidity. As a result it is recommended to operate the regenerator on drier return room air in a building application. Volumetric air flow and volumetric water flow in the heating circuit has marginal impact on regenerator capacity in the IDCS design. However, the volumetric water flow does influence the regenerator thermal input and should be minimised. It is evident, across the conditions investigated that there is an issue of instantaneous mass balance between the dehumidifier and regenerator i.e. the mass of water vapour removed from the air in the dehumidifier does not equal the mass removed from the desiccant solution in the regenerator. As a result, the complete IDCS cannot run continuously because the solution will become weak over time. The mass imbalance issue is discussed in more detail in section 3.3.

3.3 Complete IDCS performance analysis

The performance of the IDCS is evaluated with respect to its COP_{th} and COP_{el}. The COP calculations are previously defined in Equations 10 and 11 respectively. An issue encountered with the IDCS is that an instantaneous mass balance between the dehumidifier and regenerator is not easily achievable. Mass imbalance is primarily due to the available surface area for heat and mass exchange in the regenerator being too small and an insufficient vapour pressure differential between the air and desiccant solution.

In order to regenerate the desiccant solution back to its original condition following the dehumidification process, the regenerator needs to operate for extended time periods. As a result, a theoretical adjusted thermal COP ($COP_{th,adj}$) has been proposed in Equation 12. The $COP_{th,adj}$ is a steady state value that takes into account the requirement of extended regenerator operation in order to achieve a system mass balance.

$$\mathrm{COP_{th,adj}} = \frac{\dot{Q}_{\mathrm{cooling}}}{\left(\frac{\mathrm{MRR}}{\mathrm{MAR}}\right)\dot{Q}_{\mathrm{reg}}} \qquad \mathbf{12}$$

Figure 11a shows the average $COP_{th,adj}$ and COP_{el} for 21 IDCS tests. The black horizontal lines at y=1 and y=2 mark the benchmark values for COP_{th} and COP_{el} respectively. The $COP_{th,adj}$ values range from a minimum of 0.34 to a maximum of 1.26, with an average of 0.72. A COP_{th} above 1.0 is comparable with 5.0 for a VCS driven by grid electricity, demonstrating the potential for highly efficient air conditioning with the IDCS design. Furthermore, the $COP_{th,adj}$ values are competitive with current VAS but at a smaller cooling capacity. The COP_{el} values range from a minimum of 1.38 to a maximum of 3.67, with an average of 2.5. Figure 11b demonstrates the psychrometric process of the complete IDCS, indicating the air state points in the dehumidifier, regenerator and evaporative inter-cooler. The data points in Figure 11b are taken from test seven in Figure 11a. Table 6 presents the results for six sample system tests (same sample as dehumidifier and regenerator), along with their associated absolute uncertainty.

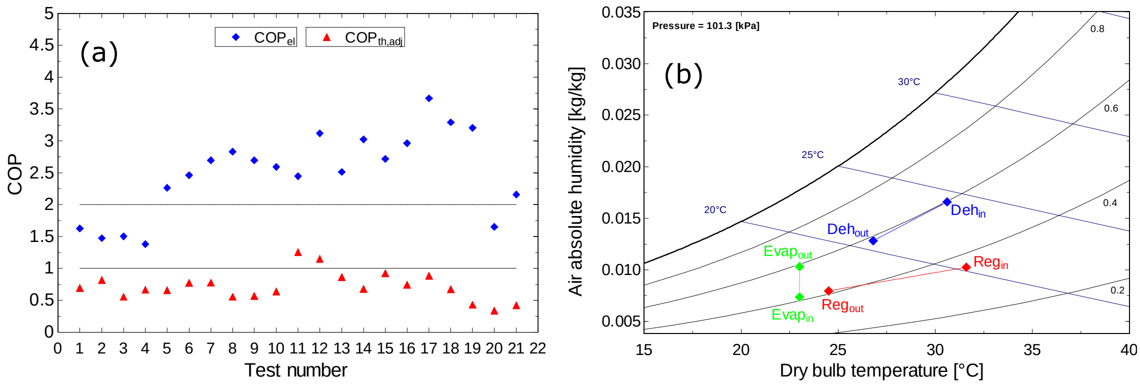

Figure 11 (a) Complete IDCS performance, and (b) IDCS psychrometric process

As the moisture addition rate in the regenerator increases, the $COP_{th,adj}$ increases. This is due to an improved mass balance between the dehumidification and regeneration processes, leading to a lower adjusted regenerator thermal input. The two $COP_{th,adj}$ values greater than 1.0 are attained when the moisture addition rate in the regenerator is greater than $0.17g.s^{-1}$, which is achieved when the absolute humidity of the inlet air to the regenerator is less than $0.008kg_{vapour}/kg_{dryair}$. Thus, it can be concluded that the IDCS performs best when moisture addition in the regenerator is maximised, which occurs at a lower regenerator inlet air absolute humidity value. As a result, when operating the regenerator on fresh outside air liquid desiccant system performance will be poorer in hot and high humid climates. It is therefore favourable to operate the regenerator on drier return room air in such a scenario. The reasonable $COP_{th,adj}$ values demonstrate the potential of the IDCS design in building applications. Across all IDCS tests the maximum calculated relative uncertainties in the IDCS $COP_{th,adj}$ and COP_{el} were ±27.73% and ±15.93% respectively.

Table 4 Samples of dehumidifier performance data and associated uncertainty

Sample number	$T_{a,in,deh}$ (°C)	$RH_{a,in,deh}$ (%)	X_{sol}	$T_{sol,deh}$ (°C)	MRR ($g.s^{-1}$)	Δω (kg/kg)	η_L (%)	$Q_{cooling}$ (W)	$T_{a,out,deh}$ (°C)
1	30.19 ± 0.2	51.37 ± 1.7	0.66	25.25 ± 0.5	0.15 ± 0.052	0.0019 ± 0.00065	30.02 ± 8.50	580 ± 143	27.77 ± 0.2
2	30.71 ± 0.2	60.43 ± 1.7	0.66	25.39 ± 0.5	0.28 ± 0.054	0.0036 ± 0.00068	38.06 ± 5.73	994 ± 153	27.23 ± 0.2
3	30.14 ± 0.2	70.72 ± 1.7	0.67	25.08 ± 0.5	0.42 ± 0.060	0.0055 ± 0.00073	45.36 ± 4.85	1045 ± 162	30.61 ± 0.2
4	36.18 ± 0.2	50.08 ± 1.7	0.66	27.68 ± 0.5	0.26 ± 0.067	0.0034 ± 0.00086	32.27 ± 6.57	1177 ± 188	29.79 ± 0.2
5	35.39 ± 0.2	60.33 ± 1.7	0.67	25.71 ± 0.5	0.36 ± 0.070	0.0047 ± 0.00089	31.91 ± 4.97	1201 ± 193	31.79 ± 0.2
6	34.70 ± 0.2	70.56 ± 1.7	0.67	25.78 ± 0.5	0.45 ± 0.073	0.0060 ± 0.00091	34.14 ± 4.26	1318 ± 198	32.77 ± 0.2

Table 5 Samples of regenerator performance data and associated uncertainty

Sample number	$T_{a,in,reg}$ (°C)	$RH_{a,in,reg}$ (%)	MAR ($g.s^{-1}$)
1	25.80 ± 0.2	47.75 ± 1.7	0.11 ± 0.057
2	23.49 ± 0.2	44.09 ± 1.7	0.14 ± 0.049
3	25.49 ± 0.2	37.95 ± 1.7	0.19 ± 0.056
4	23.96 ± 0.2	38.95 ± 1.7	0.20 ± 0.052
5	25.23 ± 0.2	44.33 ± 1.7	0.18 ± 0.055
6	24.09 ± 0.2	62.74 ± 1.7	0.12 ± 0.056

Table 6 Samples of total system performance data and associated uncertainty

Sample number	$COP_{th,adj}$	COP_{el}
1	0.58 ± 0.30	1.48 ± 0.36
2	0.69 ± 0.25	2.49 ± 0.38
3	0.53 ± 0.16	2.62 ± 0.40
4	1.19 ± 0.33	3.01 ± 0.48
5	0.76 ± 0.24	2.99 ± 0.48
6	0.41 ± 0.19	3.28 ± 0.49

4 Conclusions

To date, the application of liquid desiccant air conditioning in smaller (domestic) built environment applications has been limited. This is primarily due to large system size and complexity, issues of desiccant solution leakage and carry-over and equipment corrosion. As a result, a novel IDCS has been developed with the aim of overcoming these barriers and facilitating the wider use of the technology in building applications. The IDCS combines the regenerator, dehumidifier and evaporative inter-cooler into a single HMX. The IDCS design reduces overall system size and limits the amount of piping, heat exchangers and pumps. A semi permeable micro-porous membrane is used to prevent desiccant solution entrainment in the supply air stream.

The paper has presented an evaluation, based on experimental data, of the novel IDCS operating with an environmentally friendly $CHKO_2$ desiccant working fluid. Over the investigated environmental and operating conditions the dehumidifier performs well with the $CHKO_2$ solution. Dehumidification capacity increases with inlet air temperature, relative humidity and air volumetric flow. However, a significant conclusion from the work presented is that an instantaneous mass balance between the dehumidifier and regenerator is challenging under most conditions. Across the variables investigated there is a greater instantaneous moisture removal rate in the dehumidifier than moisture addition rate in the regenerator. As a result, a theoretical adjusted thermal COP ($COP_{th,adj}$) has been presented which takes into account the requirement of extended regenerator operation in order to achieve a mass balance. The IDCS performs best when moisture addition in the regenerator is maximised, which occurs at a lower regenerator inlet air absolute humidity value. Across all tests performed an average $COP_{th,adj}$ of 0.72 has been achieved.

This paper has demonstrated that the novel IDCS design and operating concept is viable. No previous work has been found in the literature regarding such an integrated design and thus the work provides progress to the field of liquid desiccant air conditioning technology for building applications. Future work should focus on increasing the regenerator to dehumidifier HMX surface area ratio and improving heat transfer rates to the regenerator air stream to improve system mass balance.

5 Nomenclature

$CaCl_2$ = Calcium Chloride

$CHKO_2$ = Potassium Formate

COP_{el} = electrical coefficient of performance

COP_{th} = thermal coefficient of performance

$COP_{th,adj}$ = adjusted thermal coefficient of performance

c_p = specific heat capacity ($J.kg^{-1}.K$)

h = specific enthalpy of air ($J.kg^{-1}$)

HVAC = heating, ventilation and air conditioning

IDCS = integrated desiccant air conditioning system

LiBr = Lithium Bromide

LiCl = Lithium Chloride

$\dot{m}$ = mass flow rate ($kg.s^{-1}$)

MAR = moisture addition rate in the regenerator ($g.s^{-1}$)

MRR = moisture removal rate in the dehumidifier ($g.s^{-1}$)

p_{atm} = atmospheric pressure (101325 Pa)

p_{sol} = vapour pressure of desiccant solution (Pa)

$\dot{Q}_{cooling}$ = dehumidifier cooling output (W)

$\dot{Q}_{evap}$ = evaporative cooler output (W)

$\dot{Q}_{reg}$ = regenerator thermal input (W)

RH = relative humidity (%)

T = temperature (°C)

u = velocity ($m.s^{-1}$)

v = volumetric flow ($L.min^{-1}$)

V' = volume (m^3)

VAS = vapour absorption system

VCS = vapour compression system

$\dot{W}_{aux,des}$ = IDCS electrical requirement (W)

X_{sol} = desiccant solution mass concentration

Subscripts

a = air

w = water

sol = desiccant solution

in = inlet

out = outlet

eq = equilibrium

Greek letters

η_L = latent (dehumidifier) effectiveness (%)

ρ = density (kg.m^{-3})

ω = air absolute humidity (kg$_{vapour}$/kg$_{dryair}$)

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