

DESICCANT COMPOSITION AND USE THEREOF

Field of Invention

- 5 The present invention relates to a desiccant composition, to a dehumidifier comprising the desiccant composition, to a counter-flow dew-point evaporative cooler, and to an air cooling system comprising the dehumidifier and/or the evaporative cooler.

Background

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In hot and humid climates, the energy consumed by heating, ventilation and air-conditioning (HVAC) typically comprises up to 50% of the total energy consumption in a building. Of the HVAC-related energy consumption, 55% is for the chiller. Therefore, the energy efficiency of the chiller is of high importance to ensure that the overall HVAC system is efficient and environmentally friendly.

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Conventional work-driven air conditioning systems have a thermodynamic limit of 0.45 kW/Rton at a standard rating condition, where the outlet temperature of chilled water and inlet cooling water temperature are 12.2°C and 29.4°C, respectively. Additionally, there are concerns about ozone depletion and greenhouse effect caused by the HCFC/CFC refrigerants used in such systems.

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One environmentally friendly type of cooling system are evaporative coolers, which do not require CFC refrigerants or energy-intensive compressors. Rather, evaporative coolers utilise the cooling effect of evaporation of a fluid such as water. Air can be passed over a water source, causing the water to evaporate which cools the surrounding environment/surfaces. Evaporative coolers can be classified as direct evaporative coolers (DEC), in which the working fluids (water and air) are in direct contact. and indirect evaporative coolers (IEC), where a surface/plate separates the working fluids. In an IEC, the evaporation of water cools the separating surface/plate, which then cools air flowing on the other side of the surface/plate. An issue with DEC is that the humidity of the output air is increased due to contact with the evaporating water, meaning that the output air may be uncomfortably humid. IECs do not suffer from this issue because the cooling effect is provided through a separating surface/plate, and the humidity of the output air is unchanged.

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However, a drawback of indirect evaporative coolers is that they are not suitable for tropical conditions that have high humidity, such as in Singapore. This is because the evaporative

cooling potential decreases with higher humidity (the rate of evaporation is lower), and so the cooling effect is limited in a narrow temperature range. Additionally, because IECs only sensibly cool the air, the product air's humidity ratio is as high as that of inlet air. Therefore, with an air input of high humidity the product air is often out of the thermal comfort zone.

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Known IECs include Coolers from Coolerado, USA. The Coolerado cooler is a cross-flow IEC. Cross-flow is unfavourable pattern of heat exchangers because the product air is not fully cooled and requires a high working air flowrate. This leads to a lower cooling capacity. In addition, the cross-flow configuration leads to a large size and low effectiveness of the heat exchanger. As explained above, the Coolerado cooler is not suitable for use in high humidity tropical environments.

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Another known IEC is Airbitat Smart Cooler from ST Engineering, Singapore. As for the Coolerado air conditioner, it is not suitable for tropical condition with high humidity of inlet air. As the result, its cooling capacity is low and product air is out of the human comfort zone.

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There is therefore a need for an environmentally friendly cooling system suitable for use in high humidity tropical environments.

20 **Summary of Invention**

The performance of an IEC can be improved by drying the inlet air. Therefore, in order to enlarge the evaporative cooling potential of IECs the present inventors have developed a new desiccant composition. Compared with commercial silica-gel, the desiccant composition has much high water sorption capacity and can be regenerated at lower temperature. This allows the regeneration to be performed using energy from solar collectors or low quality waste heat.

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Thus, a first aspect of the invention provides the following:

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1. A desiccant composition comprising a superabsorbent polymer and a hygroscopic material.

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2. The desiccant composition according to Clause 1 wherein the superabsorbent polymer is selected from one or more of the group consisting of polyvinyl alcohol and a polyacrylate.

3. The desiccant composition according to Clause 1 or 2, wherein the polyacrylate is selected from one or more of the group consisting of sodium polyacrylate and potassium polyacrylate.
- 5 4. The desiccant composition according any one of the preceding Clauses wherein the hygroscopic material is selected from one or more of the group consisting of a salt and a glycol.
- 10 5. The desiccant composition according to Clause 4 wherein the salt is an inorganic salt, optionally wherein the salt is selected from one or more of the group consisting of lithium chloride, calcium chloride, and sodium bromide.
- 15 6. The desiccant composition according to Clause 4 wherein the salt is an organic salt, optionally wherein the salt is potassium formate.
7. The desiccant composition according to Clause 4, wherein the glycol is selected from one or more of the group consisting of triethylene glycol, polyethylene glycol, diethylene glycol, ethylene glycol and tetraethylene glycol.
- 20 8. The desiccant composition according to any one of the preceding Clauses wherein the weight ratio of superabsorbent polymer to hygroscopic material is from about 10:1 to about 1:2, optionally about 5:1 to about 1:1.5, for example about 2.5:1 to about 1:1.1.
- 25 9. The desiccant composition according to any one of the preceding Clauses wherein the hygroscopic material is dispersed within the superabsorbent polymer.
10. The desiccant composition according to any one of the preceding Clauses further comprising an antibacterial agent.
- 30 11. The desiccant composition according to Clause 10 wherein the antibacterial agent is selected from one or more of the group consisting of ammonia, trimethylamine, acetic acid, an anilide, a biguanide, a heavy metal, a phenol and a cresol.
- 35 12. The desiccant composition according to Clause 10 or 11, wherein the antibacterial agent is present in an amount of from 1 to 5 wt% compared to the total weight of the composition.

13. The desiccant composition according to any one of the preceding Clauses wherein:

- 5 (a) the superabsorbent polymer is polyvinyl alcohol and the hygroscopic material is lithium chloride, optionally wherein the weight ratio of polyvinyl alcohol to lithium chloride is from about 5:1 to about 1:2, such as from about 2.5:1 to about 1:1.1, particularly from about 3:2 to about 1:1; or
- (b) the superabsorbent polymer is sodium polyacrylate and the hygroscopic material is lithium chloride, optionally wherein the weight ratio of sodium polyacrylate to lithium chloride is from about 5:1 to about 1:2, such as from about 2.5:1 to about 1:1.1, particularly from about 3:2 to about 1:1; or
- 10 (c) the superabsorbent polymer is polyvinyl alcohol and the hygroscopic material is potassium formate, optionally wherein the weight ratio of polyvinyl alcohol to potassium formate is from about 10:1 to about 5:1, such as about 7:1 to about 5:1; or
- 15 (d) the superabsorbent polymer is sodium polyacrylate and the hygroscopic material is potassium formate, optionally wherein the weight ratio of sodium polyacrylate to potassium formate is from about 5:1 to about 1:2, such as from about 2.5:1 to about 1:1.1, particularly about 1:1.

The desiccant compositions of the present invention are useful in desiccant-based dehumidifiers. Thus, a second aspect of the invention provides the following:

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14. A dehumidifier comprising a desiccant composition as described in any one of Clauses 1 to 13.

25 15. The dehumidifier according to Clause 14 comprising a desiccant wheel coated with the desiccant composition.

16. The dehumidifier according to Clause 14 or Clause 15 comprising a plate fin heat exchanger comprising fins coated with the desiccant composition.

30 17. The dehumidifier according to Clause 16 comprising at least two plate fin heat exchangers, each comprising fins coated with the desiccant composition.

In addition, the invention also relates to an evaporative cooler that has improved cooling performance compared to standard evaporative coolers. The evaporative coolers of the invention have a counter-flow configuration which improves cooling performance and

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reduces the volume of the cooler. Thus, a third aspect of the invention provides the following:

18. A counter-flow dew-point indirect evaporative cooler comprising:

5 a heat exchanging chamber separated by one or more channel plates, where each channel plate is arranged to provide at least one product channel and at least one working channel adjacent to one another,

where the at least one product channel has an air inlet at a first end and a product air outlet at a second end,

10 where the at least one working channel has a product air inlet formed through at least one channel plate bordering the working channel at an end region proximal to the product air outlet of the at least one product channel, and a working air outlet at an end region distal to the product air inlet;

at least one water supply means or apparatus;

15 a blower configured to propel air to the air inlet of the at least one product channel and thereby through the product air outlet of the at least one product channel, and the product air inlet and working air outlet of the at least one working channel; wherein:

20 each channel plate has a first surface facing into the at least one product channel that is, or is coated in, a water-impervious material and a second surface facing into the at least one working channel that may be, or may be coated with, a wicking material, provided that at least one channel plate surface in each working channel is, or is coated with, a wicking material; and

25 the water supply means or apparatus is configured such that it can supply water to the wicking material on the second surface of each of the one or more channel plates.

30 19. The counter-flow dew-point indirect evaporative cooler according to Clause 18, wherein the means for supplying water to the wicking material is a first water tank, and the first water tank is configured to supply water to the wicking material by capillary action through the wicking material.

35 20. The counter-flow dew-point indirect evaporative cooler according to Clause 19, wherein the counter-flow dew-point indirect evaporative cooler comprises two or more water tanks configured to supply water to the wicking material by capillary action.

21. The counter-flow dew-point indirect evaporative cooler according to Clause 19 or 20, wherein each water tank is located outside of the heat exchanging chamber, and the wicking material extends from the heat exchanging chamber to each water tank, or is connected to a piece of wicking material which extends to each water tank.

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22. The counter-flow dew-point indirect evaporative cooler according to any one of Clauses 18 to 21, wherein the wicking material comprises a fibre, cotton, gauze or tissue, optionally wherein the wicking material comprises a porous fibre material, such as a natural porous fibre material.

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23. The counter-flow dew-point indirect evaporative cooler according to any one of Clauses 18 to 22, wherein the water-impervious material is selected from one or more of the group consisting of a water-impervious polymer (e.g. polyethylene, polypropylene or polyvinyl chloride) and a water-impervious metal (e.g. aluminium, copper or stainless steel).

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24. The counter-flow dew-point indirect evaporative cooler according to any one of Clauses 18 to 23, wherein the counter-flow dew-point evaporative cooler is configured such that in operation a minor fraction of air flowing through each product channel flows through a product air inlet into a working channel, and a major fraction of air flowing through each product channel flows through the product air outlet.

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25. The counter-flow dew-point indirect evaporative cooler according to Clause 24, wherein the minor fraction of air is from 5 to 25 wt% of air passing into the dry product channel, preferably from 10 to 15 wt%.

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The desiccant composition of the invention can be used to lower the humidity of air before it passes through an evaporative cooler. For example, a hybrid system comprising an evaporative cooler and desiccant composition-based dehumidifier. Such a hybrid system, overcomes the limitations associated with the use of evaporative coolers in high humidity environments. The supply air is first dried by the dehumidifier and then sensibly cooled by the cooler. The dehumidifier not only dramatically reduces humidity of the supply air to the human-thermal comfort level, but also synergistically enhances the evaporative cooling potential for the cooler. With the help of the dehumidifier, the evaporative cooler is widely suitable for all-weather conditions. Notably, this hybrid system can be totally solar-powered and can be used as a portable air-conditioning unit for both indoor and outdoor uses.

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Thus, a fourth aspect of the invention provides the following:

26. An air cooling system comprising:
- a system inlet;
 - 5 a dehumidifier;
 - an evaporative cooler; and
 - a system outlet; wherein:
- the air cooling system comprises a fluid flow path from the system inlet to the system outlet that passes through the dehumidifier and then the evaporative cooler; and
- 10 the dehumidifier is a dehumidifier according to any one of Clauses 14 to 17.

Preferably, the system comprises a counter-flow dew-point evaporative cooler of the invention, as this type of evaporative cooler provides for improved cooling performance.

Thus, a fifth aspect of the invention provides the following:

27. An air cooling system comprising:
- a system inlet;
 - a dehumidifier;
 - an evaporative cooler; and
 - 20 a system outlet; wherein:
- the air cooling system comprises a fluid flow path from the system inlet to the system outlet that passes through the dehumidifier and then the evaporative cooler;
- the dehumidifier is a dehumidifier according to any one of Clauses 14 to 17; and
- the evaporative cooler is a counter-flow dew-point indirect evaporative cooler as
- 25 defined in any one of Clauses 18 to 25.

Although the air cooling system preferably comprises a desiccant composition of the invention (as in the fourth and fifth aspects of the invention), the invention also contemplates air cooling systems using other types of dehumidifiers. Thus, a sixth aspect of the invention

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28. An air cooling system comprising:
- a system inlet;
 - a dehumidifier;
 - 35 an evaporative cooler; and
 - a system outlet; wherein:

the air cooling system comprises a fluid flow path from the system inlet to the system outlet that passes through the dehumidifier and then the evaporative cooler; and the evaporative cooler is a counter-flow dew-point indirect evaporative cooler according to any one of Clauses 18 to 25.

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The fourth, fifth and sixth aspects of the invention also provide the following:

29. The cooling system according to any one of Clauses 26 to 28, further comprising one or more blowers configured to propel air along the fluid flow path.

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30. The cooling system according to any one of Clauses 26 to 29, further comprising a power supply for supplying power to the dehumidifier and/or evaporative cooler.

31. The cooling system according to Clause 30, wherein the power supply comprises or is connectable to one or more selected from the group consisting of a photovoltaic cell and photovoltaic thermal hybrid solar collector.

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Brief Description of the Figures

20 Figure 1 shows a testing apparatus for testing and analysing the performance of desiccant compositions. The apparatus involves passing humidified air over a desiccant coated heat exchanger (DCHE).

25 Figure 2 shows experimental results for a desiccant composition which is 70 wt% sodium polyacrylate superabsorbent polymer and 30 wt% LiCl, tested in the apparatus of Figure 1. The substantially horizontal lines depict the inlet temperature (top) and humidity (bottom). The variable lines show the outlet temperature and humidity as the desiccant is tested over several cycles.

30 Figure 3 shows experimental results for a desiccant composition which is 60 wt% sodium polyacrylate superabsorbent polymer and 40 wt% LiCl, tested in the apparatus of Figure 1. The substantially horizontal lines depict the inlet temperature (top) and humidity (bottom). The variable lines show the outlet temperature and humidity as the desiccant is tested over several cycles.

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Figures 4 to 6 show the ability of desiccant compositions according to the invention to adsorb water at different relative humidities. The y-axis shows water uptake as % by mass of desiccant composition, and the x-axis shows relative humidity at 30°C. SAP refers to sodium polyacrylate superabsorbent polymer, and PVA refers to polyvinyl alcohol superabsorbent polymer. The desiccants have adsorption capacities which are several times greater than that of silica gel.

Figures 7a-7d show advantageous properties of the desiccant composition of the invention: (a) a comparison showing that the desiccant composition of the invention has 5-7 times higher water sorption capacity than silica-gel; (b) a super absorbent coated wheel dehumidifier; (c) a comparison showing that the superabsorbent coated wheel has higher dehumidification performance than commercial silica-gel coated wheel; and (d) anti-microbial and deodorization characteristics of the desiccant comprising an antibacterial agent.

Figures 8a, 8b and 9 show different views of the arrangement of dry product channels and wet working channels within the heat exchanging chamber of a counter-flow dew-point evaporative cooler according to an embodiment of the invention.

Figure 10 shows the arrangement of water tanks and wicking material in a counter-flow dew-point evaporative cooler according to an embodiment of the invention. The wicking material extends from the wet working channels of the heat exchanging chamber and contacts the water in the water tank. Water is then transferred to the wet working channels by capillary action.

Figure 11a shows the order of components in an embodiment of the air cooling system according to an embodiment of the invention. Air is blown through a dehumidifier and then a counter-flow dew-point evaporative cooler, before being expelled as dried and cooled product air. Figure 11b shows that the cooling system of the invention is able to reduce both the temperature and humidity of air to a greater extent than several commercially available coolers (Airbitat from ST Engineering, Singapore, Coolerado from Coolerado, USA, and a conventional IEC).

Detailed Description

Desiccant compositions

The present invention provides desiccant compositions, dehumidifiers and air cooling systems which utilise the desiccant compositions. As used herein, a “desiccant composition”

is a composition which is able to absorb water from the surrounding air, thereby reducing the humidity of the surrounding air. After absorbing water, the desiccant composition will be wet and can be dried by heating. A reference to a desiccant composition herein includes a reference to the dry (e.g. anhydrous) composition, and a reference to the wet (e.g. saturated) composition, and to a partially wet desiccant composition. In embodiments, the desiccant compositions are able to absorb up to seven, such as up to five times their weight in water.

The desiccant compositions of the present invention comprise a superabsorbent polymer and a hygroscopic material.

As used herein, the word "comprising" or its analogues such as "comprises" may be interpreted as requiring the features mentioned, but not limiting the presence of other features. Alternatively, the word "comprising" may also relate to the situation where only the components/features listed are intended to be present (e.g. the word "comprising" may be replaced by the phrases "consists of" or "consists essentially of"). It is explicitly contemplated that both the broader and narrower interpretations can be applied to all aspects and embodiments of the present invention. In other words, the word "comprising" and synonyms thereof may be replaced by the phrase "consisting of" or the phrase "consists essentially of" or synonyms thereof and *vice versa*.

Suitable superabsorbent polymers for use in compositions in accordance with the invention include polyvinyl alcohol and a polyacrylate (e.g. sodium polyacrylate or potassium polyacrylate). As will be understood by a person skilled in the art, a superabsorbent polymer comprises crosslinks. As such, references to polyvinyl alcohol, polyacrylate, sodium polyacrylate, and potassium polyacrylate as being superabsorbent polymers will be understood to be references to crosslinked polyvinyl alcohol, crosslinked polyacrylate, crosslinked sodium polyacrylate, and crosslinked potassium polyacrylate. Typically, the crosslinking is performed during synthesis of the polymer. This can involve the addition of crosslinking agents. Any appropriate crosslinking agent can be used, and suitable agents include those which react with reactive groups on the polymer backbone, as well those which are themselves incorporated into the polymer backbone. Suitable crosslinking groups are known to a person skilled in the art and include ethylene glycol dimethacrylate, maleic acid and glutaraldehyde. The choice of crosslinking group will depend on the nature of the polymer backbone. For example, when the polymer is a polyacrylate, a suitable crosslinking agent is ethylene glycol dimethacrylate. When the polymer is a PVA, suitable crosslinking agents include maleic acid and glutaraldehyde.

Another method for introducing crosslinks to the polymer is free radical-based polymerisation. Radicals produced during the polymerisation process can react with a polymer chain, forming a radical in the middle of the chain (macroradical). This macroradical can react with
5 another macroradical to form a crosslinked polymer. Radicals can be formed by the inclusion of initiators (e.g. thermal initiators and photoinitiators) in the reaction mixture, or by use of high energy radiation.

10 Suitable hygroscopic materials for use in compositions in accordance with the invention include salts and glycols. The salt may be an organic salt or an inorganic salt. An example of a suitable organic salt is potassium formate. Examples of suitable inorganic salts include lithium chloride, calcium chloride, and sodium bromide, such as lithium chloride. Particular examples of suitable glycols include triethylene glycol and polyethylene glycol. Other glycols could also be used, such as diethylene glycol, ethylene glycol and tetraethylene glycol.

15 The desiccant composition may comprise an antibacterial agent. As used herein, the term "antibacterial agent" means any agent or chemical which is able to provide an antibacterial effect, such as inhibiting or preventing the growth of bacteria and/or killing bacteria.

20 The inclusion of an antibacterial agent has the effect of cleaning air passing over the desiccant composition, as well as drying, thereby reducing unpleasant odours. This also helps to avoid the build-up of bacteria or mould in the damp environment within a dehumidifier or system as a whole. Examples of suitable antibacterial agents which can be included in the desiccant compositions include ammonia, trimethylamine, acetic acid, an
25 anilide, a biguanide, a heavy metal, a phenol and a cresol.

In embodiments of the invention, the superabsorbent polymer is selected from one or more of polyvinyl alcohol and polyacrylate, the hygroscopic material is selected from one or more of lithium chloride, lithium bromide, calcium chloride, triethylene glycol and poly ethylene
30 glycol, and the antibacterial agent is selected from one or more of anilides, biguanides, heavy metals and phenols and cresols.

In some embodiments of the invention, the superabsorbent polymer is polyvinyl alcohol.

35 In some embodiments of the invention, the superabsorbent polymer is sodium polyacrylate.

In some embodiments of the invention the hygroscopic material is lithium chloride or potassium formate.

In a particular embodiment of the invention, the superabsorbent polymer is polyvinyl alcohol
5 and the hygroscopic material is lithium chloride.

In an alternative particular embodiment of the invention, the superabsorbent polymer is sodium polyacrylate and the hygroscopic material is lithium chloride.

10 The weight ratio of superabsorbent polymer to hygroscopic material is from about 10:1 to about 1:2, optionally about 5:1 to about 1:1.5, for example about 2.5:1 to about 1:1.1. As used herein, the term "about" when applied to a weight ratio means a weight ratio which deviates by up to 10% from the specified ratio. When the superabsorbent polymer is polyvinyl alcohol and the hygroscopic material is potassium formate, the weight ratio of
15 $\text{HCO}_2\text{K}:\text{PVA}$ is preferably less than 1:5, in order to ensure that the prepared solution is homogenous.

Typically, the majority of the desiccant composition is made up of the superabsorbent polymer and hygroscopic material, and so the desiccant compositions according to the
20 invention typically comprise from 20-60 wt% hygroscopic material and from 40-80 wt% superabsorbent polymer, compared to the total weight of the composition. In embodiments, the desiccant compositions comprise from 30-50 wt% hygroscopic material and 50-70 wt% superabsorbent polymer, compared to the total weight of the composition.

25 When an antibacterial agent is included in the desiccant, it is generally included in an amount of from 0.1 to 10 wt%, such as 1-5 wt%, compared to the total weight of the composition. In a particular embodiment, the desiccant composition comprises 1-5 wt% of antibacterial agent, 30-50 wt% of hygroscopic material and 45-69 wt% of superabsorbent polymer, compared to the total weight of the composition.

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As will be understood by a person skilled in the art, references to weight percent of the superabsorbent polymer and hygroscopic material refer to weight percentages of the dry polymer/hygroscopic material.

35 In some embodiments, the desiccant composition comprises a superabsorbent polymer and a hygroscopic material, and is substantially free of porous siliceous material. As used herein, "substantially free of porous siliceous material" means that the desiccant composition

comprises less than 5 wt% of porous siliceous material, for example less than 3 wt%, less than 1 wt%, less than 0.5 wt%, or less than 0.1 wt%, compared to the total weight of the composition.

5 In embodiments of the invention the desiccant composition consists essentially of a superabsorbent polymer and a hygroscopic material, optionally further including an antibacterial agent as defined herein. In such embodiments, at least 90 wt% of the composition may be made up of the superabsorbent polymer, hygroscopic material and optional antibacterial agent, for example at least 95 wt%, at least 97 wt%, at least 98 wt%, at
10 least 99 wt%, at least 99.5 wt% or at least 99.9 wt%, compared to the total weight of the composition.

The hygroscopic material is typically dispersed throughout the superabsorbent polymer matrix.

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The performance of desiccant compositions can be analyzed using the experimental set up shown in Figure 1. Outdoor air 101, and optionally indoor air 102 (when valve 103 is open) can be collected and taken into an air heater 104. The air may be humidified by an ultrasonic humidifier 105 before passing into a desiccant coated heat exchanger 106. Reference
20 samples may bypass the heat exchanger through by-pass line 107. The heat exchanger 106 comprises a desiccant to be tested, as well as temperature controlled water pipes. The temperature of the water may be controlled by the cold water bath 108, hot water bath 109 and water valve control mechanism 110. A fan 111 helps drive air through the testing apparatus and supply air 112 can be analyzed.

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Dehumidifier

The invention also provides a dehumidifier that comprises a desiccant composition according to the invention. Desiccant based dehumidifiers are well known to a person skilled in the art, who would readily be able to adapt common designs for desiccant dehumidifiers to
30 include the desiccant composition of the invention.

One type of dehumidifier in accordance with the present invention comprises a plate-fin heat exchanger comprising fins coated with the desiccant composition. In this type of dehumidifier, moist air is blown across the fins and is dried by the desiccant. A cooling fluid is
35 simultaneously supplied through the channels to capture the exothermic heat of sorption released during the dehumidification process. Warm fluid (e.g. water) may then be passed through channels located on the other side of the fins to the desiccant, warming and drying

the desiccant. Since the process operates in cycles and not continuous, a plate fin heat exchanger type dehumidifier will typically comprise at least two heat exchangers, such that one heat exchanger can perform a drying function (generating wet desiccant) whilst the desiccant on the other heat exchanger is dried. By the time the desiccant performing the drying function is close to saturation, the desiccant on the other heat exchanger will be dry. The mode of each heat exchanger can then be swapped over such that the dry desiccant performs a dehumidification function and the wet desiccant is dried. This means that the dehumidifier can run almost continuously, except for a brief time period where each heat exchanger switches function.

Another type of dehumidifier in accordance with the present invention includes a desiccant wheel coated with the desiccant composition. In this type of dehumidifier, moist air is passed through a section of the wheel, and is dried by the desiccant. The wheel slowly rotates such that the now wet section of desiccant moves away from the moist air source and a new, dry, portion of desiccant is exposed to continue drying the air. Warm air is passed through another part of the desiccant wheel to dry the wet desiccant before it returns to be exposed to the humid air.

An example of a desiccant wheel type dehumidifier 700 is shown in Figure 7b. Inlet air flow 705 flows towards a drying portion 710 of the desiccant wheel 700, where water vapour/moisture is removed, resulting in a dry air flow 720 that exits the desiccant wheel 700. This air may then be directed towards a counter-flow dew-point evaporative cooler. As the desiccant wheel 700 has a finite capacity to adsorb water, the desiccant will need to be regenerated, which may be achieved by regenerating the desiccant by directing dry, heated air (730; e.g. from 50-60°C when using the desiccant composition according to the invention) through a regeneration portion 740 of the desiccant wheel, whereby the dry, heated air 730 exits the desiccant wheel 700 through the regeneration portion 740 as humid air 750 that is typically expelled into the environment. As shown, the desiccant wheel 700 may be fitted with a motor 760 and drive system 770 to rotate the desiccant wheel so that all of the desiccant is rotated between the drying portion 710 and the regeneration portion 740 of the desiccant wheel 700.

Thus, in an embodiment the invention provides a dehumidifier comprising a desiccant wheel 700 coated in the desiccant composition. In a further embodiment, the dehumidifier also comprises a motor 760 and drive system 770 for rotating the wheel.

Counter-flow dew-point evaporative cooler

Also provided by the present invention is a counter-flow dew-point evaporative cooler. A counter-flow dew-point evaporative cooler comprises generically two or more air flowing channels and three air flowing streams, namely, (i) the supply/intake air, (ii) the product/output air, and (iii) the working air (Figures 8a, 8b and 9). The supply air to be cooled is pushed through the dry (product) channel where its temperature is lowered by water evaporation that occurs inside the adjacent wet (working) channel. Part of this conditioned air (typically a major portion) is extracted as chilled product air whilst the remaining portion is employed as the working air to perform the evaporative cooling in the wet channel. Evaporation of water in the wet channel is primarily influenced by the partial pressure difference of water vapour between the air stream and the saturated air in the boundary layer of water film. As such, if the supply air is dried with a dehumidifier, this increases the rate of evaporation in the wet channel. The working air is almost saturated before leaving the channel, and is expelled as wet exhaust air. With such an arrangement, a sizable fraction of the initial supply air can be cooled to approach its dew point, a process differing from the conventional evaporative cooling.

Thus, in an aspect of the present invention (with reference to Figures 8a, 8b and 9), there is provided a counter-flow dew-point indirect evaporative cooler comprising:

a heat exchanging chamber 800 separated by one or more channel plates 809, 909, where each channel plate 809, 909 is arranged to provide at least one product channel 801, 901 and at least one working channel 802, 902 adjacent to one another,

where the at least one product channel 801, 901 has an air inlet 805, 905 at a first end and a product air outlet 806, 906 at a second end,

where the at least one working channel has a product air inlet 807, 907 formed through at least one channel plate 809, 909 bordering the working channel 802, 902 at an end region proximal to the product air outlet 806, 906 of the at least one product channel 801, 901, and a working air outlet 808, 908 at an end region distal to the product air inlet 807, 907;

at least one water supply means or apparatus;

a blower configured to propel air to the air inlet of the at least one product channel and thereby through the product air outlet 806, 906 of the at least one product channel 801, 901, and the product air inlet 807, 907 and working air outlet 808, 908 of the at least one working channel; wherein:

each channel plate 809, 909 has a first surface 803, 903 facing into the at least one product channel that is, or is coated in, a water-impervious material and a second surface 804, 904 facing into the at least one working channel that may be, or may be coated with, a

wicking material 1001, provided that at least one channel plate surface in each working channel is, or is coated with, a wicking material; and

the water supply means or apparatus is configured such that it can supply water to the wicking material on the second surface 804, 904 of each of the one or more channel
5 plates 808, 809.

The counter-flow dew-point evaporative cooler devices of the current invention will now be discussed in more detail by reference to the embodiment shown in Figures 8a, 8b and 9. As depicted, the counter-flow dew-point evaporative cooler generally comprises a heat
10 exchanging chamber 800 comprising pairs of dry 801, 901 and wet 802, 902 channels with a stacked arrangement within a heat exchanging chamber 800. Each dry 801, 901 and wet 802, 902 channel is separated by a separating, or channel, plate 809, 909.

The dry 801, 901 and wet 802, 902 channels are stacked in an alternating arrangement,
15 such that, apart from the channels that define the boundaries of the heat exchanging chamber, each dry channel 801, 901, is sandwiched between two wet channels 802, 902 and *vice versa*. It will be appreciated that a device having a single dry channel 801, 901 and a single wet channel 802, 902 would also be expected to work in the manner described herein. While the channels shown in Figures 8a, 8b and 9 are stacked in a vertical
20 arrangement (i.e. the channel plate(s) 809, 909 are arranged horizontally), it will be appreciated that the channels may be arranged in any suitable orientation that may work. For example, in other embodiments contemplated herein, the channel plates 809, 909 may be arranged vertically, such that the channels are arranged in a horizontal manner in the heat exchanging chamber.

25 The separating (channel) plate 809, 909 between each dry 801, 901 and wet 802, 902 channel has a first surface 803, 903 facing into the dry product channel that is, or is coated in, a water-impervious material and a second surface 804, 904 facing into the wet working channel that may be, or may be coated with, a wicking material.

30 Supply input air 805a, 905a supplied from a blower (not depicted) enters the dry channel 801, 901 through an air inlet 805, 905. In aspects and embodiments of the invention where the counter-flow dew-point indirect evaporative cooler is coupled with a dehumidifier, this air may have been subjected to drying before it enters the air inlets 805, 905 of the evaporative
35 cooler. As the input air passes through the dry channel it loses heat to the wet channel 802, 902. The heat loss includes loss of sensible heat to air in the wet channel and latent heat to water on the wicking material. As the input air reaches the end of the dry channel 801, 901,

part of it will pass through the product air outlet 806, 906 as cooled product air 806a, 906a. Another part of the input air reaching the end of the dry channel will move through the product air inlet(s) 807, 907 into the wet channel 802, 902, where it will then move in the opposite direction (i.e. counter-flow) through the wet channel and hence increase the rate of water evaporation from the wet surface(s) 804, 904 of the wet channels until it passes through the working air outlet(s) 808, 908 as exhaust working air 808a, 908a. The product air inlet(s) 807, 907 are arranged in a portion of the separating/channel plate 809, 909 that is adjacent to the product air outlet 806, 906. The working air outlets 808, 908 are arranged such that the exhaust working air 808a, 908a does not re-enter the cooler as input air. This can be achieved by use of an exhaust pipe/vent or other means to prevent mixing of input air and exhaust air.

As will be appreciated, to ensure that a suitable division of the product air at the end of the dry channel 801, 901, the product air outlet and the product air inlets are sized appropriately. For example, to ensure that at least some of the product air is diverted through the product air inlets, the product air outlet may have a constrained opening (e.g. it has a dimension that is smaller than the supply air input 805, 905 into the dry channel). Similarly, when only a small proportion of the conditioned air is required in the wet channel 802, 902, the product air input(s) 807, 907 are generally one or more small holes in the channel plate 809, 909. This ensures that the majority of the product air eventually exits through the product air output 806, 906.

The portion of conditioned air which is extracted into a wet channel to be used as working air is typically from 5-60 vol%. The amount extracted as working air will depend on the requirements of the cooler. For example, the more humid the input air, the less water per unit air can evaporate into the air as it passes through the wet channel. This means that for a more humid air input, a higher air throughput is required in the wet channel in order to obtain satisfactory cooling performance. For drier input air, more water per unit is able to evaporate in the working channel, and a lower throughput of air is required. In embodiments, the proportion of air taken into the wet channel is from 5-25 vol%, for example from 10-15 vol% of the conditioned air. In other embodiments the proportion of air taken into the wet channel is from 25-60 vol%. Typically, the counter-flow dew-point evaporative cooler is used with a dried input air source, and only a small amount of air is required in the wet channels. This allows for around 75-95%, for example 85-90% of the supply air to be expelled as conditioned product air. The amount of air taken into the wet channel can be increased by using a suction fan at the end of the wet channel to withdraw the exhaust air. Similarly, the amount of air expelled as product air can be increased by using a suction fan at the end of

the dry channel to withdraw the product air. If a fan is present at the end of a dry and wet product channel, the respective speeds of the fans can be used to adjust the proportion of air flowing through each channel.

- 5 The the water-impervious material may be selected from one or more of the group consisting of a water-impervious polymer (e.g. polyethylene, polypropylene or polyvinyl chloride) and a water-impervious metal (e.g. aluminium, copper or stainless steel).

10 As discussed above, each dry channel has one or more product air inlet(s) formed through the separating (channel) plate into a wet channel, the product air inlet being located at an end region proximal to the product air outlet of the dry channel. Each channel plate may have just a single product air inlet, connecting it to one dry channel. Alternatively, a wet channel may have more than one product air inlet, for example one inlet for each dry channel that borders the wet channel. Generally, a wet channel will be bordered by two dry
15 channels (e.g. one above and one below when the channel plates are oriented horizontally, or one left and one right when the channel plates are oriented vertically). However, a wet channel could be bordered on four sides by a dry channel in a chequered arrangement, and in this case each wet channel could have product air inlets connecting it to four dry channels.

20 In order to function, the cooler device described herein also requires a means or apparatus to supply water to the wicking materials in the wet channels. This is necessary in order to replace the water which is lost due to evaporation in the cooler. Thus, the cooler also includes a water supply means or apparatus that is configured to supply water to the wicking material in the wet working channel when the device is in operation. Any suitable means of
25 supplying water to the wicking material may be employed. However, the water supply means typically comprises one or more (e.g. at least two) water tanks arranged to supply water to the wicking materials.

For example, a portion of the wicking material may extend beyond (e.g. through) the
30 boundary of the heat exchanging chamber to contact water held in the water tank. Water is drawn into and through this wicking material by capillary action, thereby allowing water to saturate the wicking materials present in the wet channels. The wicking material which extends to the water tank may be the same piece of wicking material that lines the working channel. For example, the wicking material in the wet channels may be a sheet of material,
35 and the wicking material extending out of the heat exchanging chamber may be the same sheet or may be strands formed from the same piece of material. Alternatively, the wicking material extending out of the heat exchanging chamber may be a separate piece of wicking

material that is attached to the wicking material in the working channel. When two or more pieces of wicking material are attached together, they may be attached by any means which permits the wicking of water through the material and from one piece of material to another, e.g. sewn together.

5

Figure 10 shows an example of a cooler having water tanks according to this embodiment of the invention. Wicking material (capillary clothes) 1001 extend through the boundary of the heat exchanging chamber 1002 and into the water tanks 1003. When the water tank contains water, the capillary clothes 1001 will contact the water, and water will be transported through the capillary clothes to the wet channels by capillary action.

10

As will be appreciated by a person skilled in the art, each layer of wicking material present in the working channel is connected to (or is part of) a piece of wicking material that extends to a water tank. This means that water can be supplied to every layer of wicking material within the working channels.

15

The wicking material may be selected from, but not limited to, one or more of a fibre, cotton, gauze or tissue material, for example a porous fibre material, such as a natural porous fibre material.

20

The cooler also comprises one or more blowers (e.g. a fan) which propels air through the cooler. For example, the blower may be configured to propel air to the air inlet of the at least one product channel and thereby through the product air outlet of the at least one product channel, and the product air inlet and working air outlet of the at least one working channel.

25

Counter-flow dew-point evaporative coolers according to the invention have been shown to have a wet-bulb effectiveness of up to 105-115% and dew-point effectiveness of up to 80-90% (see examples below). Compared with the Coolerado cooler, the counter-flow IEC of the invention has ~15-20% higher cooling capacity and 15-25% higher dew-point and wet-bulb effectiveness, respectively, when tested with input air having a temperature of $32 \pm 3^\circ\text{C}$ and humidity ratio of $22 \pm 3 \text{ g/kg}$.

30

While the counter-flow dew-point evaporative coolers may be particularly useful in combination with the desiccant and dehumidifiers described herein, they may also be used alone to provide a cooling effect in areas that may benefit from such as system. For example outside areas. In such cases, the counter-flow dew-point evaporative coolers of the present

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invention may be powered by one or more photovoltaic cells, such that they are energy efficient.

Air cooling systems

5 With reference to Figure 11a, the present invention also provides an air cooling system. The system comprises a system inlet 1101, which may comprise a blower to assist the intake of air. A dehumidifier 1102 is placed before an evaporative cooler 1103. The efficiency of an evaporative cooler decreases as the humidity of the air increases because the rate of evaporation is lower at higher humidity. This problem can be solved by placing a
10 dehumidifier before the evaporative cooler, which dries the air 1104 before it flows into the evaporative cooler. This results in a higher rate of evaporation within the working channels of the evaporative cooler, thereby increasing the cooling performance, as well as reducing the humidity of the output air to more pleasant levels.

15 The effect of using a dehumidifier in a cooling system can be seen in Figure 11b. The dehumidifier latently cools the air, increasing the dry bulb temperature but significantly reducing humidity. The counter-flow dew-point evaporative cooler then sensibly cools the air, resulting in cool, dry product air that is within the thermal comfort zone. This is in contrast with commercially available coolers which produce cooler air having a high relative humidity
20 outside the thermal comfort zone.

Generically, an air cooling system of the invention comprises:

a system inlet;
a dehumidifier;
25 an evaporative cooler; and
a system outlet; wherein:
the air cooling system comprises a fluid flow path from the system inlet to the system outlet that passes through the dehumidifier and then the evaporative cooler.

30 Various combinations of dehumidifier and evaporative cooler are possible. The following cooling systems are contemplated within the scope of the present invention:

- (a) a system comprising a dehumidifier of the present invention, and an evaporative cooler;
- 35 (b) a system comprising a dehumidifier, and a counter-flow dew-point evaporative cooler of the present invention; and

(c) a system comprising a dehumidifier of the present invention, and a counter-flow dew-point evaporative cooler of the present invention.

The system may further comprise a power supply or means for providing power to the dehumidifier and/or evaporative cooler, for example a solar-based power supply, such as a photovoltaic cell and/or a photovoltaic thermal hybrid solar collector. Alternatively, the system may comprise electrical contacts to which a power supply may be connected. As will be understood by a person skilled in the art, the dehumidifier and counter-flow dew-point evaporative cooler as described herein may also comprise such a power supply or means for providing power.

As well as one or more blowers being present in the counter-flow dew-point evaporative cooler, the system and dehumidifier of the invention may comprise one or more blowers. The purpose of a blower is to propel air through the system and dehumidifier. An example of a suitable blower is a fan. In an embodiment of the invention, a blower is located at the system inlet to assist the intake of air.

Advantages of the present invention

- The desiccant composition, dehumidifier, counter-flow dew-point evaporative cooler, and cooling system of the invention have a number of advantages.
- The desiccant composition has a higher water sorption ability than traditional desiccants such as silica and zeolite. This allows for the use of a smaller quantity of desiccant (reducing size and weight), while allowing increased performance.
 - The desiccant composition can be dried/regenerated at a lower temperature (e.g. 50-60°C) than traditional desiccants which generally require temperatures of over 100°C. This means the desiccant composition requires less energy to dry and can be dried using environmentally friendly options, such as solar power or waste heat sources.
 - The desiccant can be easily coated onto a variety of materials without requiring a binder. In contrast, traditional desiccants such as silica or zeolite require a binder to be coated onto a surface.
 - The desiccant has anti-bacterial and deodorisation properties due to the hygroscopic nature of the components, and this can be further enhanced by including an anti-bacterial agent. This means that air cooling systems and dehumidifiers comprising the desiccant output product air which is both dry and clean.

- The counter-flow dew-point indirect evaporative cooler, has a number of advantages compared to other cooler systems.
 - Direct evaporative coolers expose the supply air to the water which is to evaporate, therefore increasing the humidity of output air. Further, the exposure of the output air to the wet interior of the cooler increases the risk of spread of bacteria and mould.
 - A counter-flow evaporative cooler is more compact than a traditional cross-flow cooler, while having higher cooling capacity. Cross-flow coolers typically result in air which is not fully cooled and require a high flow rate of working air.
 - The evaporative cooler does not require an energy intensive mechanical compressor, meaning that it can be powered by solar power or waste heat sources.
 - The evaporative cooler does not require moving parts other than air blowers, increasing reliability and ease of manufacture.
- The cooling system is highly compact, portable and versatile. The dehumidifier can be smaller than traditional dehumidifiers due to the increased performance of the desiccant. The counter-flow design of the evaporative cooler is more compact than traditional cross-flow designs.

Examples

General method for preparation of desiccant composition coated surface

A powder of a superabsorbent polymer is added in distilled water, and an appropriate quantity of hygroscopic material is then added to the mixture to achieve the desired ratio. Alternatively, the hygroscopic material can be dissolved first, followed by addition of the superabsorbent polymer. Depending on the amount of superabsorbent polymer required, it can be added to the solution in parts. The mixture is then stirred continuously at elevated temperature, such as 80°C, for 5-6 hours until a homogeneous solution is obtained.

30

This homogenous solution can be coated onto a surface and dried as set out below.

First, the surface is cleaned in distilled water and dried at 60-70°C for 1 hour.

If the surface is metallic, it should be protected with an anti-corrosion material (e.g. polyvinylidene fluoride) before being coated with desiccant composition. This can be done by

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dipping the surface into a solution containing 3-5% of polyvinylidene fluoride in a mixture of dimethylformamide/acetone (1:1), then drying the surface at 100°C for 1 hour.

5 The desiccant coating process is then performed by running the prepared desiccant composition solution over the surface. After that, a blower is used to blow the excess solution off from the surface, which is then dried in at 100°C for 2-3 hours.

10 In order to determine the amount of desiccant composition which has coated the surface, the part can be weighed before and after coating, and the amount of the desiccant-coated on the surface is noted. The coating process is generally carried out multiple times until the desiccant is coated in an amount of about 50-60 g/m².

Example 1: PVA and LiCl (2:1) desiccant composition solution

15 In 50 ml of water, add 2.5 g of polyvinyl alcohol superabsorbent polymer and 1.25 g of lithium chloride powders. Stir this mixture at 80°C for 5-6 hours to get a homogeneous gel solution which can be coated on a surface using the above general protocol.

Example 2: Sodium polyacrylate and LiCl (1:1) desiccant composition solution

20 In 100 ml of water, add 2.5 g of LiCl and mix it manually with a stirrer.
Add 1.5 g of sodium polyacrylate superabsorbent polymer in the LiCl solution and stir this mixture at 80°C for 2-3 hours.
Further, add 1 g of sodium polyacrylate superabsorbent polymer (total 2.5 g) and continue
25 stirring in the same conditions until a homogeneous gel solution is obtained.

Example 3: Sodium polyacrylate and LiCl (3:2) desiccant composition solution (2.5 litres)

In 2500 ml of distilled water, add 33.33 g of LiCl. Stir the mixture manually at room temperature for about 5-10 minutes to obtain a homogeneous LiCl solution.
30 Add about 15 g of sodium polyacrylate superabsorbent polymer in the LiCl solution and magnetically stir at 80°C for 2-3 hours.
Add another 15g of sodium polyacrylate superabsorbent polymer and continue stirring under the same conditions for another 2-3 hours.
Add another 10g of sodium polyacrylate superabsorbent polymer and continue stirring under
35 the same conditions for another 2-3 hours.
Finally, add 10 g of sodium polyacrylate superabsorbent polymer and continue to stir until a homogeneous gel solution is obtained.

Example 4: PVA and HCO₂K (5:1) desiccant composition solution

In 50 ml of water, add 2.5 g of PVA superabsorbent polymer and stir this mixture at 80°C for 2-3 hours

- 5 Prepare a solution of HCO₂K in water by adding 0.5 g of HCO₂K in 30 ml of water.
Mix the two solutions and continuously stir it at 80°C for 1-2 hours until a homogeneous gel solution is obtained.

Example 5: Sodium polyacrylate and HCO₂K (1:1) desiccant composition solution

- 10 In 50 ml of water, add 0.5 g of HCO₂K and stir it manually for about 5 mins.
In the solution, add 0.5 g of sodium polyacrylate superabsorbent polymer and stir the mixture at 80°C for 2-3 hours until a homogeneous gel solution is obtained.

Example 6: Performance of a desiccant composition coated heat exchanger

- 15 A plate fin heat exchanger was coated with sodium polyacrylate-LiCl desiccant compositions containing 30 wt% and 40wt% LiCl. The desiccant compositions were prepared according to the method of Example 3 (adjusting the amount of the sodium polyacrylate superabsorbent polymer and lithium chloride as necessary). The heat exchanger was incorporated into the
20 desiccant coated heat exchanger testing system shown in Figure 1.

The performance of the desiccant compositions is shown in Figures 2 and 3. The desiccant compositions were able to reduce the humidity of the air from 22 g/kg to 15.2 g/kg (30 wt% LiCl), and from 21.5 g/kg to 16.5 g/kg (40 wt% LiCl).

25

Sodium polyacrylate-LiCl (30 wt%)Inlet Conditions

Parameter	Value	Unit
Inlet Temperature/ $T_{a, in}$	~30	°C
Inlet air humidity ratio/ $\omega_{a, in}$	~22	g/kg
Cycle time/ t_{cycle}	15	min
Cooling water temperature/ $T_{cw, in}$	~20	°C
Hot water temperature/ $T_{hw, in}$	~50	°C
Air flow rate	55	kg/h
Water flow rate	4	kg/min

The averaged outlet results for three cycles were:

$$T_{a, out} = \sim 26^{\circ}\text{C}$$

$$\omega_{a, out} = \sim 15.2 \text{ g/kg}$$

5 Sodium polyacrylate-LiCl (40 wt%)

Inlet Conditions

Parameter	Value	Unit
Inlet Temperature/ $T_{a, in}$	32.3	$^{\circ}\text{C}$
Inlet air humidity ratio/ $\omega_{a, in}$	21.5	g/kg
Cycle time/ t_{cycle}	13	min
Cooling water temperature/ $T_{cw, in}$	21.05	$^{\circ}\text{C}$
Hot water temperature/ $T_{hw, in}$	45.12	$^{\circ}\text{C}$
Desiccant-air contact time	0.105	sec

Outlet results:

$$T_{a, out} = 26.65^{\circ}\text{C}$$

$$10 \quad \omega_{a, out} = 16.5 \text{ g/kg}$$

Example 7: Comparison of air cooling system of the invention with commercial coolers

Commercial evaporative coolers (Coolerado, Airbitat, and a conventional indirect evaporative cooler) were obtained from the corresponding manufacturers.

An air cooling system according to the present invention was prepared, in which the dehumidifier was a plate fin heat exchanger comprising fins coated with a desiccant composition consisting of sodium polyacrylate superabsorbent polymer (60 wt%) and lithium chloride (40 wt%). The dehumidifier was coupled to a counter-flow dew-point evaporative cooler according to the invention.

Each cooler was tested as follows. The coolers were set up and run until they reached stable operation (about 1 hour). The air temperature and humidity at different locations of the cooler are measured and recorded. The average air conditions of input and output airs are plotted in the psychrometric chart in Fig. 11a. While the output air from the commercial coolers is colder than the input air, it contains the same or higher moisture content. As a result, the commercial evaporative coolers do not produce output product air within the thermal comfort zone. In contrast, the cooling system of the present invention is able to reduce both the

humidity and temperature of the air, resulting in cooler and drier product air that is within thermal comfort zone.