NOTICE: this is the author's version of a work that was accepted for publication in International Journal of Refrigeration. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in International Journal of Refrigeration, 34, 8, (Dec. 2011). http://dx.doi.org/10.1016/j.ijrefrig.2011.06.012

Characterization of Desiccant Wheels with Alternative Materials at Low Regeneration Temperatures

Stephen D White[1*], Mark Goldsworthy[1], Roger Reece[1], Thorsten Spillmann[1], Abdullah Gorur[1] and Dae-Young Lee[2]

[1] CSIRO Energy Technology, PO Box 330, Newcastle, NSW, 2300, Australia

[2] Korea Institute of Science and Technology, PO Box 131, Cheongryang, Seoul, 130-650, Korea

[*] Corresponding Author, stephen.d.white@csiro.au ; Ph +61 2 4960 6070, Fax +61 2 4960 6054

Abstract

A number of new desiccant materials have been proposed which have the potential to improve the performance of desiccant wheels being regenerated at low temperature. Desiccant wheels containing two such desiccant materials (zeolite and super absorbent polymer) were compared with a conventional silica-gel desiccant wheel. The super absorbent polymer desiccant wheel achieved greater dehumidification than the silica gel wheel when dehumidifying high relative humidity air with low temperature (50°C) regeneration air. The temperature of dehumidified air exiting the polymer wheel was also lower. The zeolite desiccant wheel was generally less effective at dehumidifying air and had a higher pressure drop.

Keywords: Desiccant Wheel, Dehumidification, Silica gel, Polymer, Zeolite

1. Introduction

Solid desiccant cooling has been proposed as an alternative to vapour compression refrigeration for space cooling. It is an environmentally attractive solution, which does not require ozone depleting refrigerants and can be run off low temperature waste heat or solar heat.

At the heart of the process, a desiccant wheel is used for dehumidifying building supply air, prior to an evaporative cooling step. Silica-gel is widely used as a desiccant material in the desiccant wheel, although there is an ongoing desire to develop new improved desiccant materials (Jia *et. al.*, 2007, Tokarev *et. al*., 2002, Cui *et. al.*, 2007).

Ideally an improved desiccant material would (i) lower the humidity of dehumidified air exiting the desiccant wheel (thereby increasing the efficiency of the desiccant cooling process) and (ii) increase the rate of dehumidification (thereby reducing desiccant wheel size and cost). This would be achieved with minimum pressure drop over the axial length of the desiccant wheel. Materials that enable the desiccant wheel to be regenerated with lower temperature heat are also attractive for a number of waste heat and solar thermal applications.

Three desiccant wheels with alternative low temperature desiccant materials are investigated in this study. The three materials are (i), a ferroaluminophosphate (FAM-Z01) zeolite material with 7.3 Å pore size, (ii) a super absorbent polymer and (iii) silica gel for comparison with conventional practice.

Kakiuchi *et. al.*, 2005, Oshima *et. al*, 2006 and Cho *et. al*., 2007 presented results from the testing of desiccant wheels with the FAM-Z01 zeolite material. They found that the zeolite desiccant wheel gave improved performance over a silica-gel wheel when regenerating at very low temperatures (~50ºC). Shim *et. al* 2008, compared the performance of a new superabsorbent polymer desiccant material with that of silica gel in a batch dehumidification /

regeneration desiccant process. They reported an increase in the dehumidification rate of around 20% with the superabsorbent polymer at a regeneration temperature of 60ºC.

2. Experimental Description

Experimental testing of candidate desiccant wheels was performed using the Controlled Climate Test Facility at the CSIRO Energy Centre in Newcastle, Australia. The facility (Figure 1) is designed to provide two streams of air at controlled temperature and humidity conditions. One stream of simulated fresh "supply" air is dehumidified by the test desiccant wheel. The second stream of air, at temperatures up to 90ºC, is used for regenerating the desiccant wheel.

Each air stream is first dehumidified over a refrigerated coil before being heated and then re-humidified, by steam injection, to the desired level. A final trim heater is used to achieve the desired temperature. The two conditioned air streams are supplied to the desiccant wheel inlet faces. The dehumidified supply air and spent moist regeneration air streams exiting the desiccant wheel are removed and exhausted out of the laboratory.

The temperature of each of the inlet and outlet air streams was sampled at four positions across the duct cross-section to obtain a representative measurement of the bulk air stream conditions. Temperature was measured with class B RTD temperature sensors. Sensor error was small compared with the variation of temperature across the duct cross-section (around ±1.2 K). This temperature variation across the duct cross section is due to stratification and uneven heating/ humidification across the duct.

The humidity of each of the inlet and outlet air streams was measured from respective air samples taken uniformly across each duct cross-section. Sampling lines were heated to prevent moisture condensation on surfaces. Relative humidity was measured with capacitive humidity sensors (Vaisala HMW40/50) accurate to ± 1.5%RH. Each sensor was calibrated at operating conditions, for each test point, by comparison with measurements from a precision dewpoint analyser (General Eastern Optica) with dew point accurate to ±0.2 K.

The velocity of dehumidified supply air and spent moist regeneration air downstream of the desiccant wheel was calculated from the pressure drop measured over respective Venturi nozzles according to ASHRAE Standard 41.2, 1992. The pressure drop was measured with a Dwyer Series MS-121 differential pressure transmitter with an accuracy of ± 1% of full scale corresponding to an accuracy of ± 0.16 ms^{-1} for the velocity.

The pressure difference across the wheel was measured by a Dwyer Series 668-5 differential pressure transmitter with an accuracy of ± 13 Pa.

All measurements were sampled every second and logged with a LabVIEW 7.1 data acquisition system. Once all the sensor measurement readings were stable, the sample period was started and the recorded measurement was taken as the average over a 10 minute sample interval.

2.1. Low Temperature Desiccant Materials

Three desiccant wheels with alternate low temperature desiccant materials were investigated in this study. Silica gel was selected as the reference desiccant material as its performance has been well characterized. FAM-Z01, a ferroaluminophosphate zeolite material, with 7.3 Å pore size, was chosen as a second desiccant material for investigation. Kakiuchi *et. al.*, 2005 reported on the physical properties and vapour isotherms of the FAM zeolite material, concluding that it has high adsorption capacity over a very narrow range of operating relative vapour pressure.

The third low temperature desiccant material selected for this study was a new super absorbent polymer (SAP) desiccant material obtained by ion modification from the polyacrylicacid. The equilibrium sorption capacity of the polymer desiccant was measured at various relative humidities and at temperatures of 30°C, 40°C, and 50°C. Within the 5% experimental error margin, the equilibrium sorption capacity was found to be independent of temperature. The isotherm, resulting from the average of all experiments is shown in Figure 2. A typical isotherm of silica gel, obtained from open literature Dai et al., 2001, is also compared in the figure. The polymer desiccant shows much larger sorption capacity than silica gel at most relative humidity conditions except at very low ones.

2.2. Test Desiccant Wheels

The silica gel, zeolite and superabsorbent polymer desiccant wheels were supplied by NovelAire, Mitsubishi Chemicals and Green Rotors respectively. The silica gel and superabsorbent polymer desiccant wheels were both 360 mm outside diameter with 80 mm hub diameter. The zeolite desiccant wheel was 300 mm outside diameter and 60 mm hub diameter. Wheel face area was divided 50% dehumidification/ 50% regeneration for all of the tested desiccant wheels

Care was taken to minimise leakage across seals within the manufacturers design. Rubber seals were used for (i) sealing around the perimeter of the silica gel wheel, and (ii) sealing across the face of the zeolite and silica-gel desiccant wheels. Brush seals were used for (i) sealing around the perimeter of the zeolite and polymer desiccant wheels and (ii) sealing across the face of the polymer wheel.

A damper was placed in the supply air exhaust flow stream. This created a flow resistance and a resulting backpressure on the supply air such that any possible leakage across seals would result in flow from the supply air side to the regeneration air side. In this way, possible contamination of the supply air with regeneration air was prevented.

2.3. Test Conditions

The aim of the experiments was to characterise the performance of the desiccant wheels across ambient and regeneration air heat source conditions likely to be encountered over a typical year when using a flat plate solar hot water system as the heat source. The selected nominal values for the test variables in each test series are presented in Table 1. For each test series, data was gathered over a range of relative humidities between 20% and 90%. In all cases, the regeneration and supply air inlet absolute humidities were set equal. Initial tests investigating the performance at different rotational speeds found that 20 rph (revolutions per hour) was near optimum for all desiccant wheels and so this speed was subsequently fixed for all the tests reported in this study.

The measured pressure drop over the axial length of the desiccant wheels, at a superficial face velocity of 2.5 ms^{-1}, was 180, 260, and 150 Pa for the silica gel, zeolite and polymer wheels respectively.

3. Experimental results

3.1. Comparison with manufacturer data – silica gel wheel

A typical series of results, showing the influence of inlet air humidity on the measured supply and regeneration air humidity, is illustrated in Figure 3. As expected, there is a corresponding increase in regeneration air humidity with a decrease in supply air humidity. The average difference, over all tests, between the measured moisture removal (dehumidification of supply air) and the measured moisture gain (humidification of regeneration air) was 0.9% ± 2.3%. No systematic bias was evident.

Figure 3 also includes the expected supply air and regeneration air outlet humidity calculated using the manufacturers calculator tool (NovelAire, 2010). It is apparent that predictions from the manufacturer's calculator are optimistic. Tests with varying backpressure on the supply air side gave similar results suggesting that leakage across seals was not a major factor.

3.2. Comparison of silica gel, polymer and zeolite wheels

The measured dehumidification performance of the three desiccant wheels is shown in Figure 4 for a supply air temperature of 20ºC and Figure 5 for a supply air temperature of 30ºC, each at a constant face velocity of 2.5 ms^{-1}.

The following trends may be observed:

i) The dehumidification performance increases significantly with increasing inlet relative humidity.

ii) The silica gel wheel outperforms the zeolite wheel under most conditions, with the exception of high humidity where they have similar performance.

iii) The super-adsorbent polymer performs slightly better (10-15%) than the silica gel wheel at low regeneration temperature (50ºC) and high inlet relative humidity (>50% at 30ºC).

iv) As the inlet air relative humidity decreases, the super-adsorbent polymer wheel dehumidification performance decreases more rapidly than the silica gel and zeolite wheel performance.

v) The amount of dehumidification achieved by the silica gel and zeolite wheels increased with higher regeneration temperature, in all cases. However, the polymer wheel does not appear to benefit as much from the higher regeneration temperature. At the 80ºC regeneration condition and for low relative humidity, the polymer wheel performance is substantially below the other two wheels.

In addition to achieving high dehumidification, in a solar cooling system it is also desirable for the supply air outlet temperature to be as cool as possible. This presents a trade-off since higher dehumidification generally leads to more supply air heating due to the effect of adsorption heating. The dehumidification is shown as a function of the supply air outlet temperature for each wheel and over all of the test cases in Figure 6.

The supply outlet air temperature from the silica gel wheel is typically higher than the other two wheels. The mean dehumidification per unit temperature rise, taken over all of the experimental tests were found to be: 0.22 gK^{-1} (silica gel), 0.31 gK^{-1} (polymer) and 0.26 gK^{-1} (zeolite).

3.3. Face velocity variations

The influence of varying the supply and regeneration face velocities was investigated for a fixed supply air temperature of 30°C and regeneration air temperature of 50°C. Figure 7 shows the dehumidification performance of the three wheels; silica gel (top), polymer (middle) and zeolite (bottom), as a function of the supply inlet relative humidity for a fixed supply inlet face velocity of 2.5 ms^{-1} and for three different regeneration face velocities of 1.5 ms^{-1}, 2.0 ms^{-1} and 2.5 ms^{-1}.

As the volume of regeneration air decreases, so too does the dehumidification performance of all the wheels. However, at high relative humidity, the polymer wheel is more strongly influenced by the available regeneration heat with approximately twice the dehumidification occurring when the regeneration air flow rate is increased from 1.5 ms^{-1} to 2.5 ms^{-1}. On the other hand, for the zeolite wheel there is only a small change in performance for variations in the regeneration air flow rate over the full range of supply inlet relative humidity.

The influence of changing *both* the supply side face velocity and the regeneration side face velocity is summarised in Figure 8 for the three wheels. For the silica gel and polymer wheels there is only a slightly better dehumidification performance for the 1.7 ms^{-1} face velocity. However, for the zeolite wheel, the 1.7 ms^{-1} face velocity leads to substantially (~25%) better performance than the 2.5 ms^{-1} face velocity.

4. Discussion

The difference between measured desiccant wheel performance, with the alternative materials, is surprisingly small given the large differences in the respective equilibrium moisture sorption capacities and isotherm shapes (eg Shim *et. al.* (2008) claim that the polymer desiccant sorption capacity is 4 to 5 times larger than silica gel).

Collier *et. al.* (1986) obtained a similar result, concluding that the water sorption capacity of the desiccant material is not nearly as important as the isotherm shape in achieving the best cooling system thermal performance. Furthermore, Collier (1988) found that isotherm shape was less important at low regeneration temperatures.

The small impact on dehumidification resulting from changing from a face velocity of 2.5 ms^{-1} to 1.7 ms^{-1}, for the silica gel and polymer desiccant wheels, suggests that heat and mass transfer resistances are relatively small in these materials. While the range of velocities investigated was not large, this is consistent with Collier (1988), who also found that heat and mass transfer resistances are relatively small.

5. Conclusions

A number of new desiccant materials have been proposed, which have the potential to improve the performance of desiccant wheels when regenerated at low temperature. In this study, desiccant wheels containing two such desiccant materials (zeolite and super absorbent polymer), were compared with a conventional silica-gel desiccant wheel.

The super absorbent polymer desiccant wheel achieved greater dehumidification than the silica-gel wheel at low regeneration temperature (50°C) and high relative humidity (>60%). However, the polymer wheel did not benefit as much from the higher (80°C) regeneration temperature as the other wheels and was more sensitive to regeneration air velocity. For a given amount of dehumidification, the dehumidified air exiting the polymer desiccant wheel was significantly cooler than air exiting the silica gel desiccant wheel.

Despite the zeolite material's previously reported high equilibrium moisture loading potential and s-shaped isotherm, dehumidification achieved by the zeolite desiccant wheel was generally less than that achieved by the silica-gel desiccant wheel. Pressure drop across the length of the wheel was also higher. Unlike the other two wheels, the level of dehumidification achieved by the zeolite desiccant wheel decreased with decreasing supply air velocity and was insensitive to regeneration air velocity.

References

ANSI/ASHRAE 41.2, 1992, "Standard methods for laboratory airflow measurement", ASHRAE: Atlanta.

Cui Q., Chen H., Tao G. and Yao H., 2007, "Performance study of new adsorbent for solid desiccant cooling", Energy, Vol. 30, pp 273-279

Cho W., Kato S., Ooka R, Tsay Y-S, Koganei M, Shoda N, and Kawamoto K, 2007, "Study on dehumidification performance of FAM-Z rotor", Proc 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings IAQVEC 2007, Sendai, Japan

Collier R.K., Cale T.S., and Lavan Z., 1986, “Advanced desiccant materials assessment, final report”, Gas Research Institute Report GRI-86/018

Collier R.K., 1988, “Advanced desiccant materials assessment. Phase 2. Final report”, Gas Research Institute Report GRI-88/0125

Dai, Y. J., Wang R. Z., and Zhang, H. F., 2001, “Parameter analysis to improve rotary desiccant dehumidification using a mathematical model”, International Journal of Thermal Sciences, Vol. 40, pp. 400-408.

Jia C.X., Dai Y.J., Wu J.Y., Wang R.Z., 2007, “Use of compound desiccant to develop high performance desiccant cooling system”, International Journal of Refrigeration, Vol. 30, 345-353

Kakiuchi H., Shimooka S., Iwade M., Oshima K., Yamazaki M., Terada S., Watanabe H. and Takewaki T.; 2005, “Novel water vapor adsorbent FAM–Z01 and its applicability to an adsorption heat pump”, *KAGAKU KOGAKU RONBUNSHU*, Vol.31, pp.361-364

Oshima K., Yamazaki M., Takewaki T., Kakiuchi H. and Kodama A., 2006, “Application of novel FAM adsorbents in a desiccant system”, *KAGAKU KOGAKU RONBUNSHU*, Vol. 32, pp.518-523.

Shim J-Y, Song G-E, and Lee D-Y, 2008, “Dehumidification and regeneration of a polymeric desiccant”, Proceedings of the International Sorption Heat Pump Conference, Seoul, Korea

Tokarev M., Gordeeva L., Romannikov V., Glaznev I. and Aristov Y., 2002, “New composite sorbent CaCl2 in mesopores for sorption cooling/heating”, International Journal of Thermal Sciences, Vol41, 470–474

Table Titles

Table 1: Experimental tests performed on each desiccant wheel

Figure Titles

Figure 1: Schematic of the Controlled Climate Test Facility. (1) Intake filter, (2) Fan, (3) Medium temperature coil, (4) Low temperature coil, (5) Primary heater bank, (6) Steam injection humidifier, (7) Secondary heater bank, (T) Temperature sensor, (RH) Relative humidity sensor, (V) Velocity sensor, (DP) Differential pressure sensor.

Figure 2: Isotherm of the polymer desiccant compared with that of silica gel

Figure 3: Comparison of measured silica-gel desiccant wheel outlet air stream humidity with values calculated using the NovelAire desiccant wheel calculator at 30°C supply air inlet temperature and 80°C regeneration air inlet temperature

Figure 4: Comparison of the dehumidification performance of silica gel, super-adsorbent polymer and zeolite desiccant wheels as a function of the supply inlet relative humidity for a fixed supply inlet temperature of 20ºC, regeneration temperatures of 50ºC and 80ºC and face velocity of $2.5ms^{-1}$

Figure 5: Comparison of the dehumidification performance of silica gel, super-adsorbent polymer and zeolite desiccant wheels as a function of the supply inlet relative humidity for a fixed supply inlet temperature of 30ºC, regeneration temperatures of 50ºC and 80ºC and face velocity of $2.5ms^{-1}$.

Figure 6: Comparison of the dehumidification performance of silica-gel, super-adsorbent polymer and zeolite desiccant wheels versus the change in supply side air temperature for a fixed supply inlet temperature of 20ºC, regeneration temperatures of 50ºC and 80ºC and face velocity of $2.5ms^{-1}$

Figure 7: Comparison of dehumidification performance of silica gel (top), polymer (middle) and zeolite (bottom) desiccant wheels for three difference regeneration air face velocities, supply air velocity of $2.5ms^{-1}$, supply air temperature of 30ºC and regeneration air temperature of 50ºC

Figure 8: Comparison of silica gel, polymer and zeolite desiccant wheel dehumidification performance with varying supply inlet relative humidity for two different face velocities (on both supply air and regeneration air sides) and with fixed supply air temperature of 30ºC and regeneration air temperature of 50ºC.

Series	1	2	3	4	5	6	7
Supply air temperature	20°C	30°C	20°C	30°C	30°C	30°C	30°C
Regeneration air temperature	50°C	50°C	80°C	80°C	50°C	50°C	50°C
Supply air face velocity	2.5 ms^{-1}	2.5 ms^{-1}	2.5 ms^{-1}	2.5 ms^{-1}	1.7 ms^{-1}	2.5 ms^{-1}	2.5 ms^{-1}
Regeneration air face velocity	2.5 ms^{-1}	2.5 ms^{-1}	2.5 ms^{-1}	2.5 ms^{-1}	1.7 ms^{-1}	2.0 ms^{-1}	1.5 ms^{-1}

Table 1 Experimental tests performed on each desiccant wheel

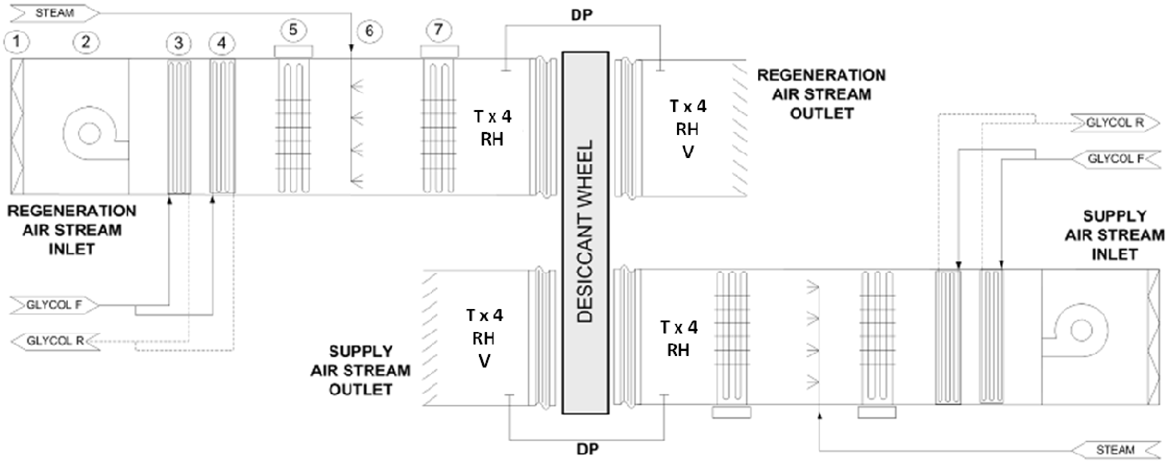

Figure 1 Schematic of the Controlled Climate Test Facility. (1) Intake filter, (2) Fan, (3) Medium temperature coil, (4) Low temperature coil, (5) Primary heater bank, (6) Steam injection humidifier, (7) Secondary heater bank, (T) Temperature sensor, (RH) Relative humidity sensor, (V) Velocity sensor, (DP) Differential pressure sensor.

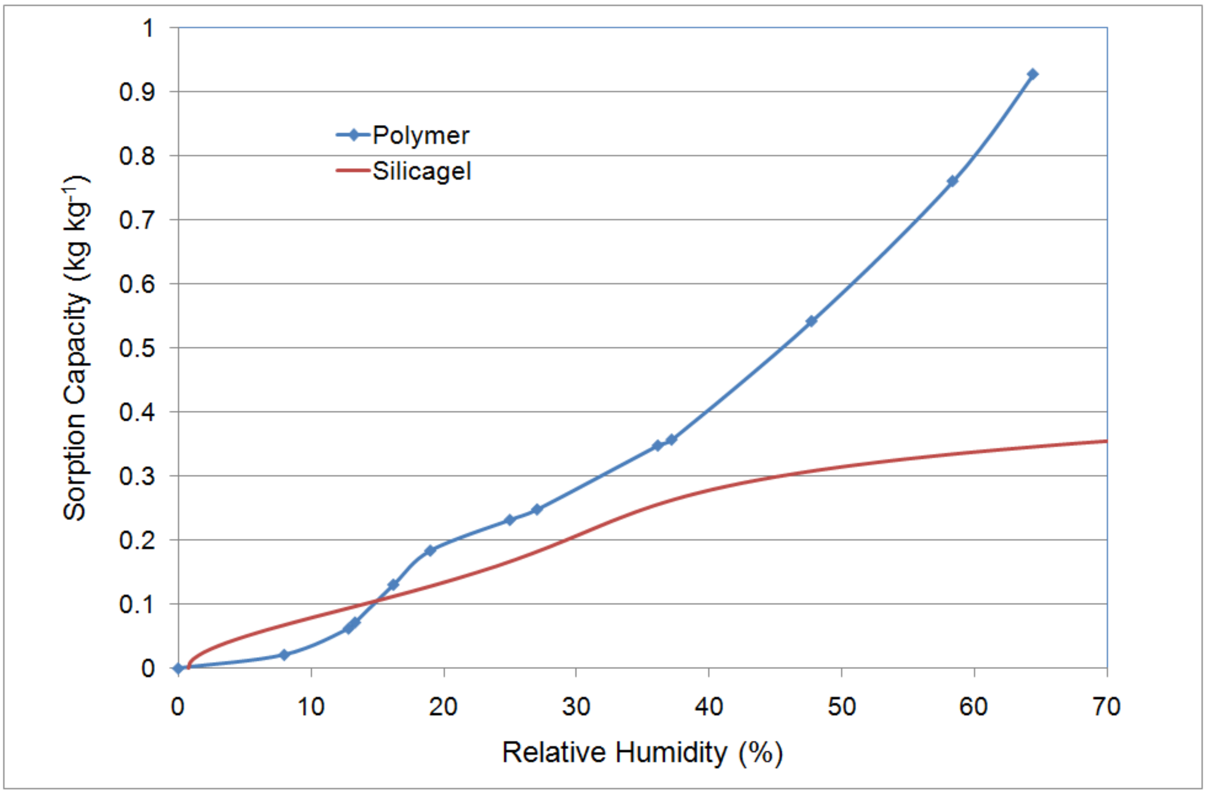

Figure 2: Isotherm of the polymer desiccant compared with that of silica gel.

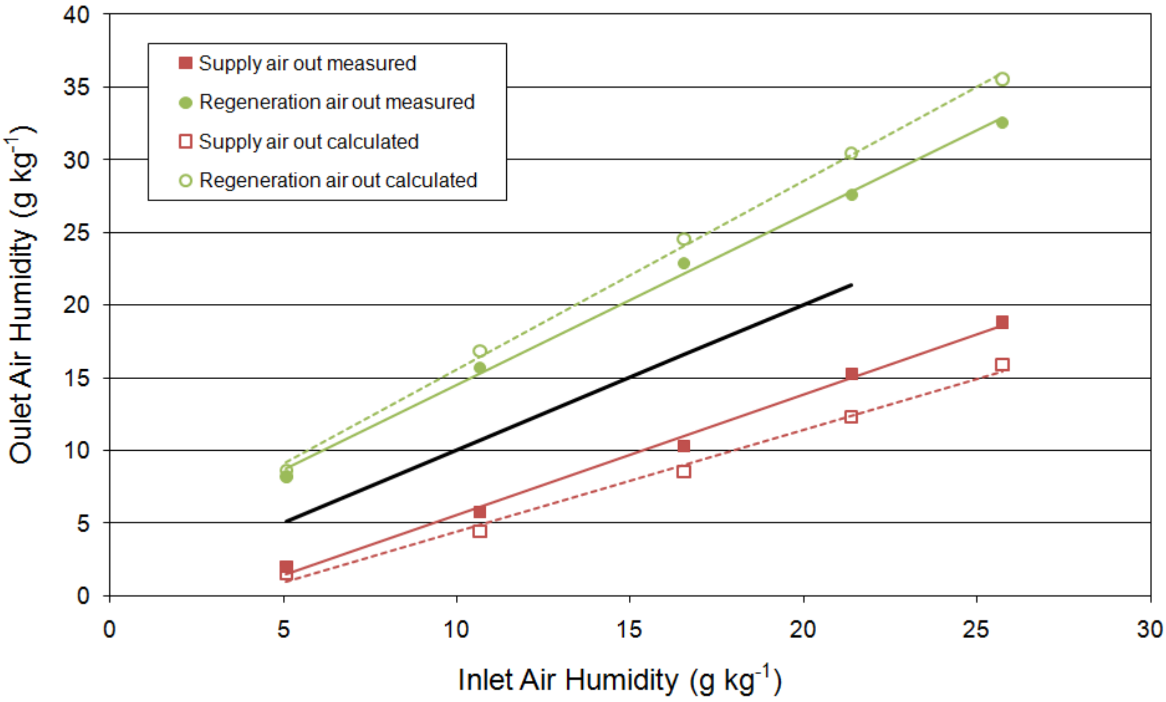

Figure 3 Comparison of measured silica-gel desiccant wheel outlet air stream humidity with values calculated using the NovelAire desiccant wheel calculator at 30°C supply air inlet temperature and 80°C regeneration air inlet temperature.

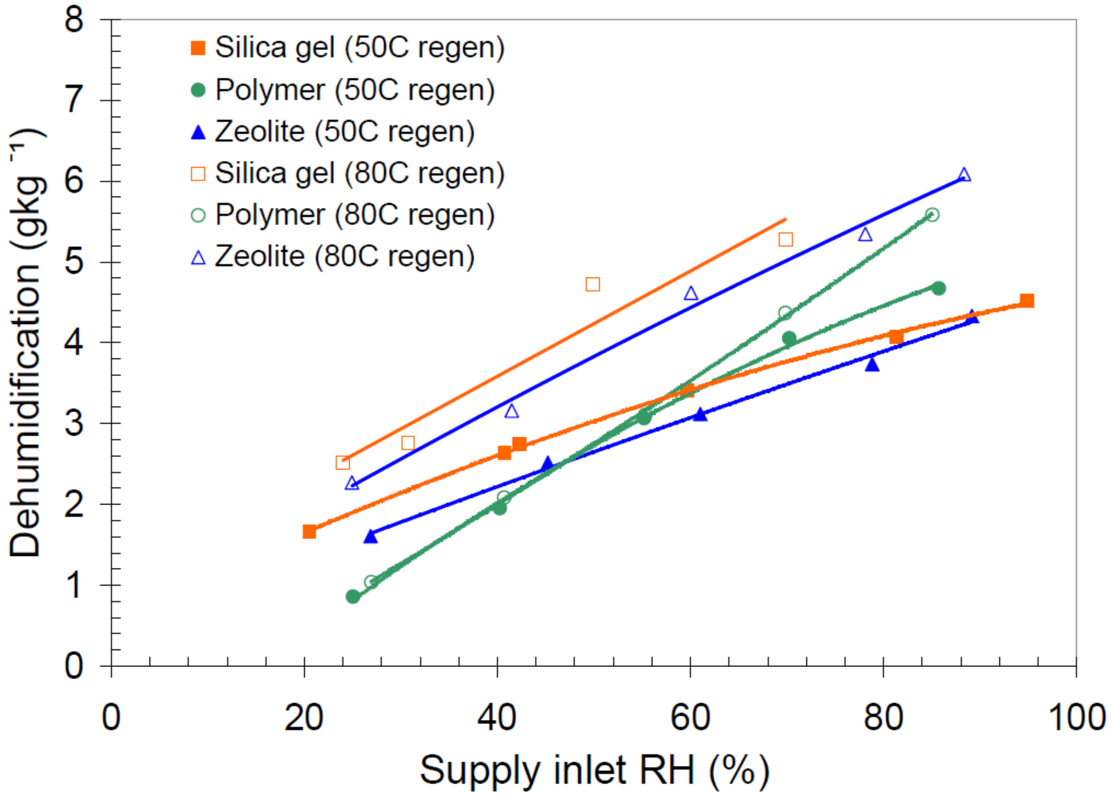

Figure 4: Comparison of the dehumidification performance of silica gel, super-adsorbent polymer and zeolite desiccant wheels as a function of the supply inlet relative humidity for a fixed supply inlet temperature of 20ºC, regeneration temperatures of 50ºC and 80ºC and face velocity of 2.5ms^{-1}.

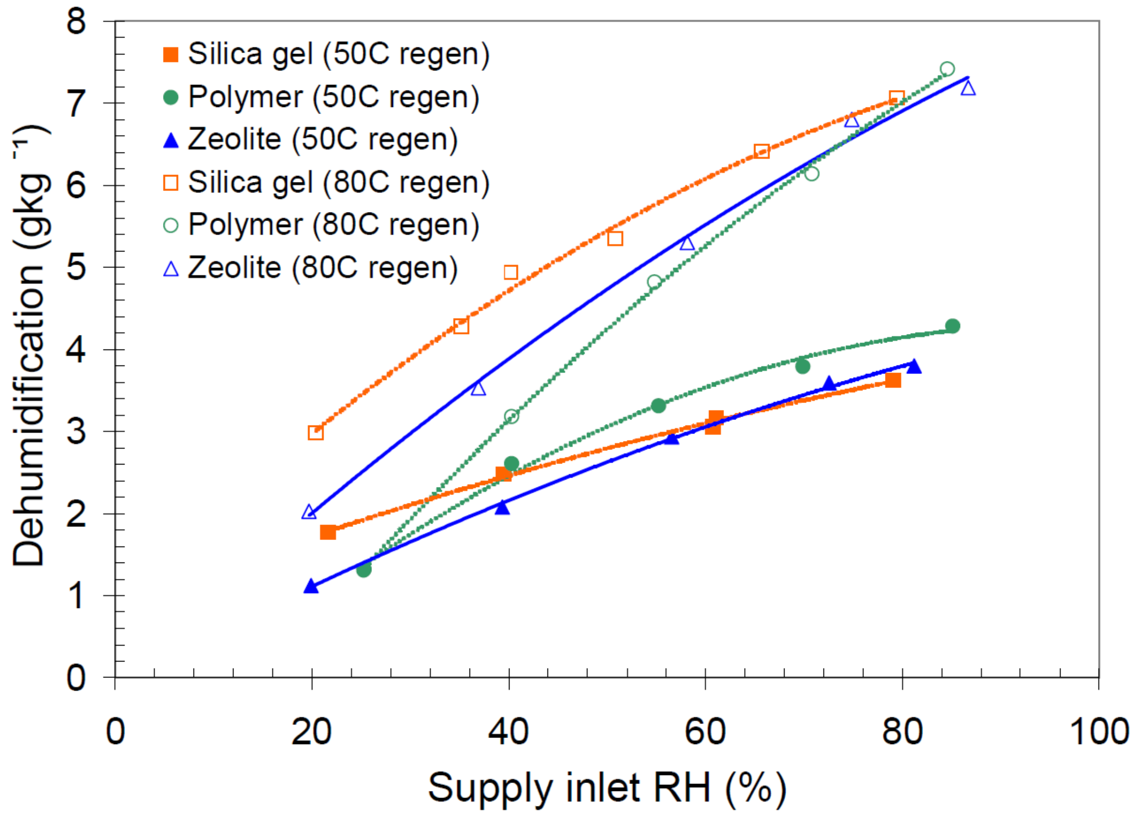

Figure 5: Comparison of the dehumidification performance of silica gel, super-adsorbent polymer and zeolite desiccant wheels as a function of the supply inlet relative humidity for a fixed supply inlet temperature of 30ºC, regeneration temperatures of 50ºC and 80ºC and face velocity of 2.5ms^{-1}.

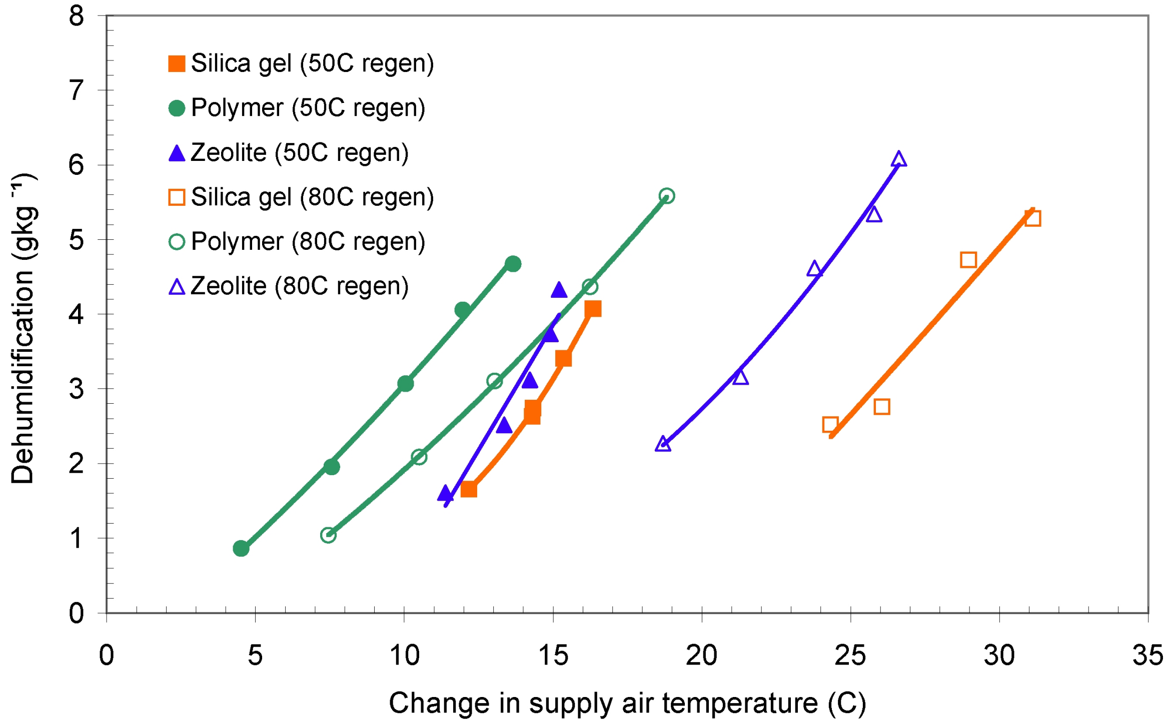

Figure 6: Comparison of the dehumidification performance of silica-gel, super-adsorbent polymer and zeolite desiccant wheels versus the change in supply side air temperature for a fixed supply inlet temperature of 20ºC, regeneration temperatures of 50ºC and 80ºC and face velocity of $2.5ms^{-1}$.

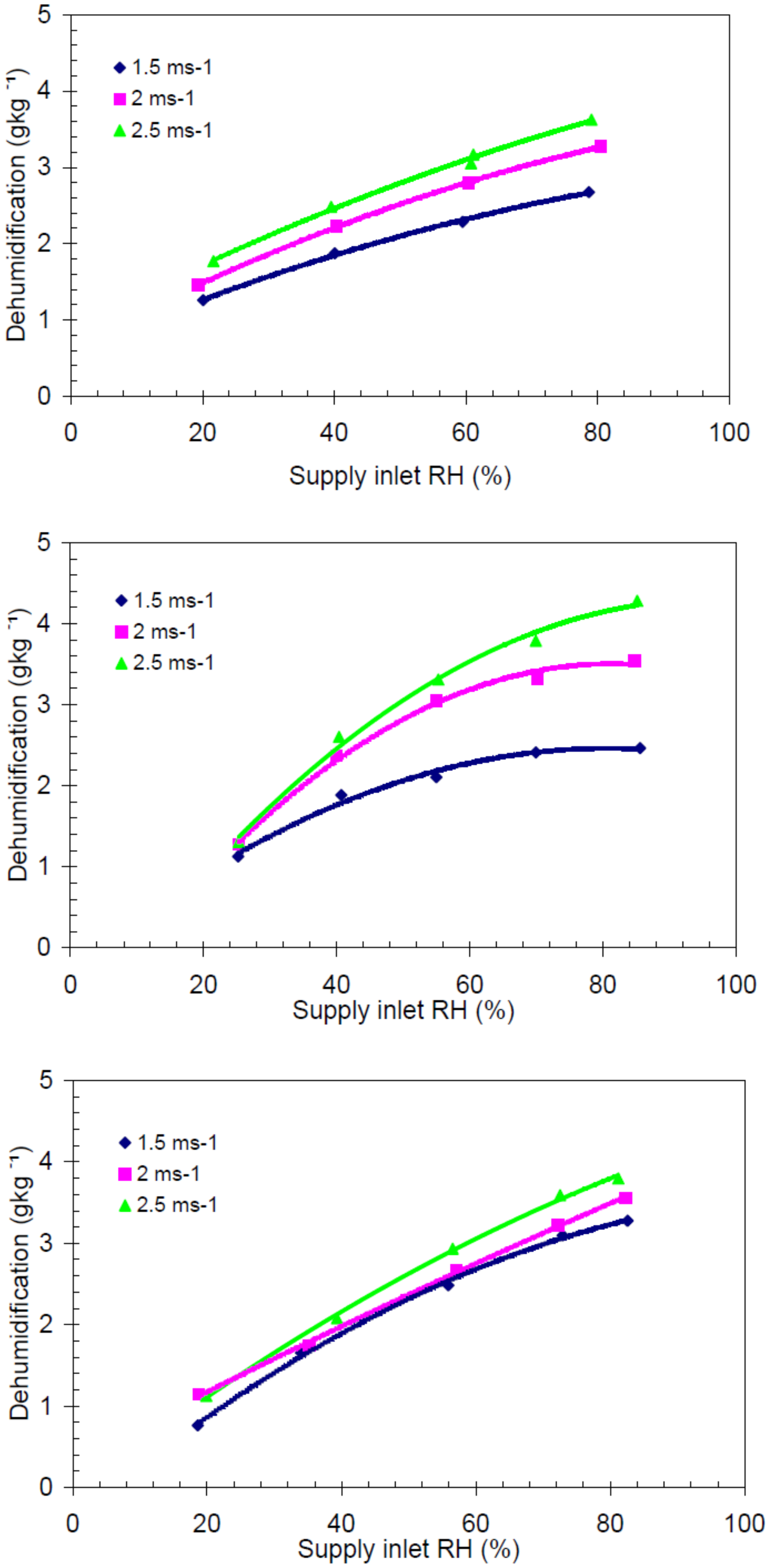

Figure 7 Comparison of dehumidification performance of silica gel (top), polymer (middle) and zeolite (bottom) desiccant wheels for three difference regeneration air face velocities, supply air velocity of 2.5ms^{-1}, supply air temperature of 30°C and regeneration air temperature of 50°C.

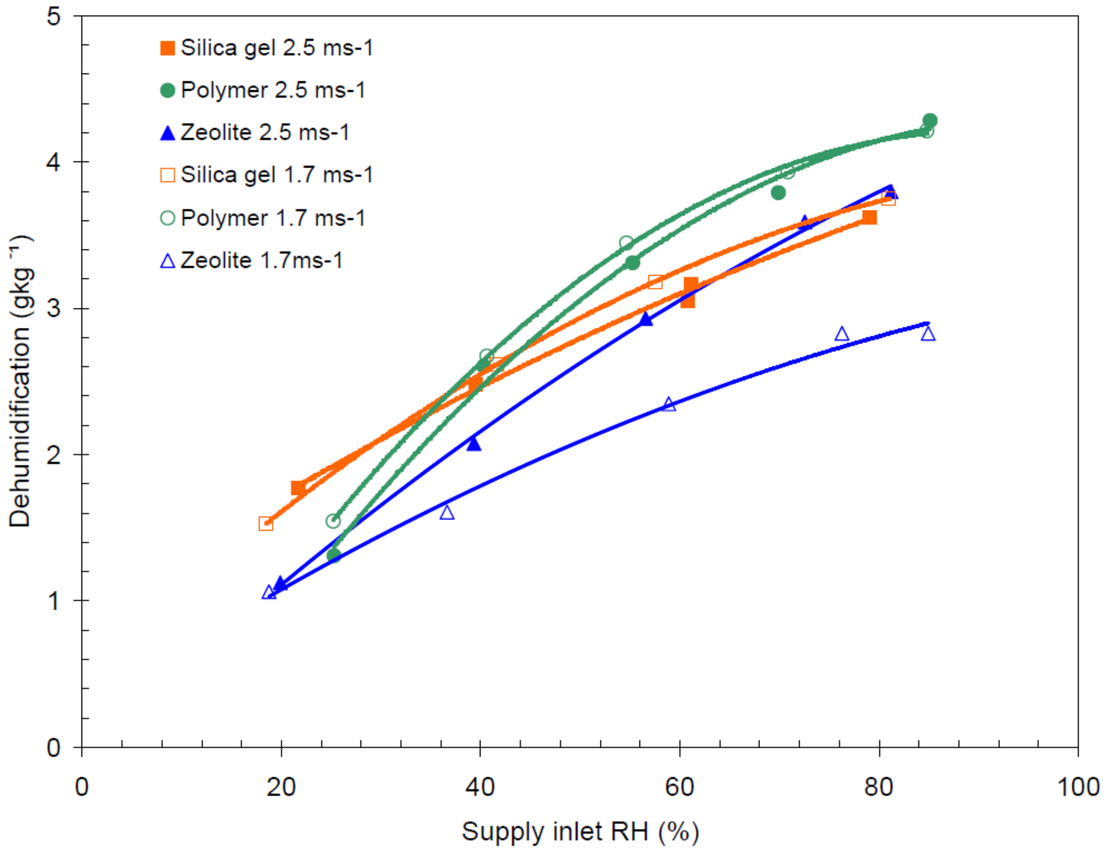

Figure 8: Comparison of silica gel, polymer and zeolite desiccant wheel dehumidification performance with varying supply inlet relative humidity for two different face velocities (on both supply air and regeneration air sides) and with fixed supply air temperature of 30^{o}C and regeneration air temperature of 50^{o}C.