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# GEL-INDUCED DEW CONDENSATION

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## Keywords

Water Harvesting; Hydrogel; Dew Condensation; Vapor Adsorption

## Highlights

- Hydrogels harvest more dew water from atmosphere than regular bare surfaces
- Dew enhancement on hydrogels is due to vapor adsorption adding to condensation

## Abstract

Hydrogels are known to adsorb a large amount of vapor and liquid water, making them good candidates to enhance the amount of dew condensed from atmosphere. Although water vapor adsorption and liquid invasion in hydrogels have been the object of many studies, water condensation has been only little investigated. We address here the process of dew

26 condensation on hydrogel grains widely used in agriculture (Aquasorb 3005<sup>TM</sup>). We show that  
27 dew condensing on hydrogels is enhanced when compared to a regular bare substrate due to  
28 vapor adsorption, which adds to condensation. Hydrogels, which can both capture water by  
29 vapor adsorption and condense water vapor with high efficiency, are thus good candidates to  
30 harvest water vapor from atmosphere with higher yield than regular bare surfaces.

31

## 32 **1. Introduction**

33

34 Hydrogels are three-dimensional networks of hydrophilic polymers, whose properties are  
35 known since more than 50 years (see e.g. Wichterle and Lím, 1960). There are many types of  
36 hydrogels (e.g. pH-, temperature-, electro- sensitive, light-responsive, etc.), with several  
37 applications related to their extraordinary swelling properties (volume can be multiplied by  
38 1000) when immersed in liquid water (for a review, see e.g. Majee, 2016; Ganji et al., 2010).  
39 The osmotic pressure attributed to the polymer network is the driving force of swelling. An  
40 osmotic gradient indeed forms between the water solvent, low in ionic solute, towards the  
41 polymer, rich in ionic solute. The swelling process distends the network and is  
42 counterbalanced by the elastic contractility of the stretched polymer network. Due to this  
43 osmotic pressure, hydrogels can also exhibit high water adsorption from water vapor (they are  
44 hygroscopic), an adsorption which increases with relative humidity  $RH$  (see e.g. Delavoipière  
45 et al., 2018), making them suitable for atmospheric water harvesting (Zhao et al., 2019).  
46 Water in hydrogels can be recovered by a moderate ( $\sim 1$  bar) osmotic mechanical pressure  
47 (Milimouk et al., 2001; Zhang et al., 2017). The osmotic pressure exerted by plant roots in  
48 presence of soil water, on the order of 0.1 - 1.2 MPa, can be high enough to extract water  
49 from the gel mixed with soil and so provide water to the plant roots (Rudzinski et al., 2002;  
50 Puoci et al., 2008). For agriculture in arid and semi-arid environments, there is an obvious

51 interest to swell the gels with water obtained at the place where they need to be used, thus  
52 preventing water transportation on long distances. In consequence, collecting water from  
53 humid air by adsorption and/or dew condensation is very appealing.  
54 The question we thus address in this study is whether, once exposed to humid air at night and  
55 cooled near or below the dew point, a typical hydrogel used in agriculture (Aquasorb 3005™)  
56 could adsorb and/or condense more water than regular surfaces do. It appears that hydrogel  
57 can indeed condense water at a larger rate than a bare substrate. In addition, when gel  
58 temperature is above the dew point temperature, water adsorption still occurs.  
59 The paper is organized as follows. After this introduction, details about the experiments and  
60 methods are given. Then the water adsorption process is studied for relative humidity lower  
61 than 100%, followed by condensation / adsorption proceeding at supersaturation larger than 1.  
62 The paper ends by some concluding remarks concerning the main results of the study.

63

## 64 **2. Experiments and methods**

65

66 The absorbent materials are samples of Aquasorb 3005™, manufactured by SNF Floeger, a  
67 granular polyacrylamide. The materials are cross-linked copolymers of acrylamide and  
68 potassium acrylate, which are water insoluble and have a very high absorption capacity (ratio  
69 water weight/hydrogel weight up to 400). Further information can be found in Table 1 and  
70 from Aquasorb 3005™ (2020). The samples can be found in three sizes presentation  
71 (Dąbrowska and Lejcuś, 2012): small-size grains (diameter  $0.19 \pm 0.07$  mm), medium-size  
72 grains (diameter  $0.70 \pm 0.2$  mm) and large-size grains (diameter  $1.5 \pm 0.4$  mm). Hereby we  
73 report results with small and medium grains.

74 The experimental apparatus is depicted in Fig. 1. It is placed inside a climatic chamber where  
75 air temperature and humidity are controlled. The setup consists of a cooling device, a silicon

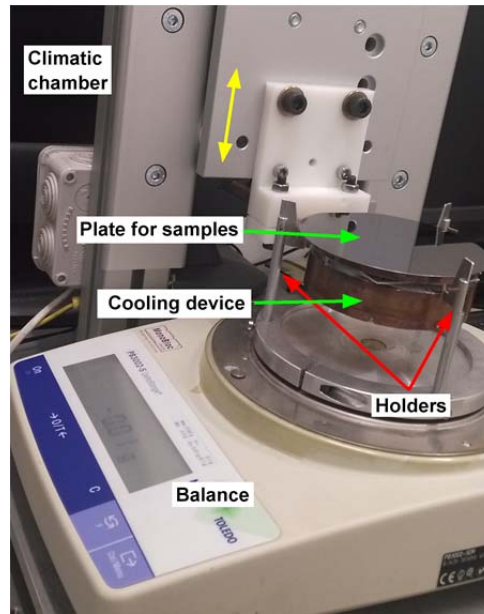
76 (Si) plate of diameter 10 cm and thickness 0.7 mm (condensing surface  $S_c = 7.853 \times 10^{-3} \text{ m}^2$ ),  
77 which holds the considered sample, and a balance to register the overall weight of sample and  
78 Si plate. The cooling device is held by a motorized support which moves it from an upper  
79 position, where it is in contact with the plate, to a lower position, where the plate is suspended  
80 by holders attached to the electronic balance and can be weighted. The Si plate is usually in  
81 contact with the cooling device. Each 38 s, the plate is moved to the lower position to be  
82 weighed, a step which lasts about 8 s. Temperature of the cooled plate is measured by  
83 calibrated thermocouples with an accuracy of 0.1 °C and a sensitivity of 0.01°C. In the  
84 chamber, air temperature  $T_a$  is set at  $20 \pm 0.5$  °C and relative humidity at  $50 \pm 3$  %, which  
85 corresponds to a vapor pressure of 1.15 kPa and a dew point temperature  $T_d = 9.3 \pm 0.1$  °C.  
86 The gel sample grains are poured on the silicon plate by the help of a circular mold which  
87 keeps the sample height less than 1 mm (small and medium grains) to form a thin layer. In  
88 order to have identical departure conditions in all cases, all the samples were previously dried  
89 at 40 °C during 8 hours and stored in a closed box with silica gel to maintain a low humidity  
90 level. For each experiment, the conditions inside the chamber and the cooling device  
91 temperature are fixed at their desired value before placing the plate with the gel.

92 Two different conditions were investigated, above or below the dew point, which corresponds  
93 to either relative humidity  $RH \leq 100\%$  (above the dew point) or supersaturation  $SR > 1$  (below  
94 the dew point). Relative humidity and supersaturation are defined from water vapor pressures  
95 as

$$97 \quad SR \text{ or } RH/100 = \frac{p(T_a)}{p_s(T_p)} \quad (1)$$

98  
99 Here,  $p(T_a)$  is the water vapor pressure in the air surrounding the plate and  $p_s(T_p)$  is the  
100 water vapor saturation pressure at substrate (plate) temperature. In addition to the

101 determination of characteristic adsorption isotherms under various  $RH$ , typical temperature  
 102 conditions as encountered at night outdoors were specially investigated: (i) Above the dew  
 103 point with a plate temperature  $T_p = T_d + 4$  K (adsorption), (ii) below the dew point :  $T_p = T_d - 4$   
 104 K.  
 105



106  
 107  
 108 Fig. 1. Experimental setup in the climatic chamber. The sample is placed on a silicon plate  
 109 cooled from below. The cooling device moves vertically (yellow double arrow). In the upper  
 110 position, the cooling device is in contact with the plate and controls its temperature. In the  
 111 lower position, the plate remains suspended from the holders fixed to the balance (red arrows)  
 112 and the weight can be measured. A thermocouple is fixed below the plate to measure its  
 113 temperature  $T_p$ .

114

| <i>Parameters</i>   | <i>small size</i> | <i>medium size</i> |
|---|-------------------|--------------------|
| Grain diameter (mm)                                       | $0.19 \pm 0.07$   | $0.70 \pm 0.20$    |
| Specific weight ( $\text{g.cm}^{-3}$ )                    |                   | 1.1                |
| Absorption capacity in 24 h.<br>(water mass/dry gel mass) | 336               | 369                |

115

116

117

118 Table 1. Some data on Aquasorb 3005<sup>TM</sup> gel (from Dąbrowska and Lejcuś, 2012 and  
119 Aquasorb 3005, 2020).

120

### 121 **3. Above the dew point**

122 The dynamics of adsorption is classically governed by two processes (see e.g. Ganji et al.,  
123 2010). One process is water molecules diffusing in the gel by Fick's law due to the difference  
124 of water concentration between humid air ( $c_0$ , corresponding to water vapor pressure  $p \sim RH$ )  
125 and water concentration in gel ( $c_c$ ). The other process is the stretching relaxation of the  
126 polymer chains.

127 For typical times corresponding to adsorption amplitudes lower than 60% of the limiting  
128 saturation value, the adsorption data measured by  $\omega_i = m_w/m_i$  ( $m$  corresponds to mass with  
129 subscript  $w$  for water and subscript  $i = s$  or  $m$  for dry small and medium size gel grains) can  
130 be fitted to the power law revealing the mode of relaxation:

131

$$132 \quad \omega_i = m_w/m_i = A_i t^x \quad (2)$$

133

134  $A_i$  is an amplitude and  $x$  an exponent whose value corresponds to the gel relaxation process.

135 For pure Fickian diffusion,  $x = 1/2$ . For pure gel relaxation,  $x = 1$ . In general, the exponent is  
136 between 1/2 and 1, corresponding to both relaxation-controlled transport and diffusion-  
137 controlled processes. Equation 2 can thus be generalized. With  $A_i, B_i$  corresponding to  
138 amplitudes related to the two processes:

139

$$140 \quad \omega_i = A_i t^{1/2} + B_i t \quad (3)$$

141

142 For adsorption amplitudes larger than 60% of the limiting saturation value, the approach to  
143 saturation can be described in the case of diffusion by the Fick's law. For a spherical particle  
144 of radius  $R$ , initial radius  $R_i$  and surface  $S = 4\pi R^2$  one obtains, neglecting the radius change  
145 in the concentration gradient as swelling remains small in the adsorption process:

146

$$147 \quad \frac{1}{S} \frac{dm_w}{dt} = -D_p \nabla c = D_p \frac{c_0 - c_c}{R} \sim D_p \frac{c_0 - c_c}{R_i} \quad (4)$$

148

149 where  $D_p$  is the water diffusion coefficient in the polymer.

150 The adsorbed mass corresponds to water concentration in the gel,  $c_c = 3 m_w / (4\pi R_i^3)$ . The  
151 solution to this equation leads to the following exponential decay evolution, in terms of ratio

152  $\omega_i$ :

153

$$154 \quad \omega_i = \omega_{i,\infty} (1 - e^{-t/\tau_i}) \quad (5)$$

155

156 Here  $\omega_{i,\infty}$  is the maximum rate of water in the saturated gel,

157

$$158 \quad \omega_{i,\infty} = \frac{4\pi R_i^3 c_0}{3m_i} \propto RH \quad (6)$$

159

160 and the typical relaxation time,  $\tau_i$ , reads as

161

$$162 \quad \tau_i = \frac{R_i^2}{3D_p} \quad (7)$$

163



164 Since the diffusion of vapor around the grains limits the process (as in the case of thin film  
 165 studies by Delavoipière et al. (2018)), the adsorption dynamics depends on the thickness of  
 166 the diffuse boundary layer, that is the layer where a Peclet number  $Pe = \frac{UL}{D} < 1$ . Here,  $U$  is  
 167 the air flow velocity far from the substrate,  $L$  is the characteristic length of the substrate and  $D$   
 168 is the diffusivity of water molecules in air. In our study, the hydrodynamic conditions are the  
 169 same for all studied substrates, small or medium grains, and difference in kinetics can be only  
 170 attributed to  $RH$  and the grain size.

171 In the case where the gel relaxation dominates the process, a relation similar to Eq. 5 is found,  
 172 however with a relaxation time which is independent of gel grain radius and relates to the  
 173 relaxation of the gel network,

174

$$175 \quad \omega_i = \omega'_{i,\infty} \left(1 - e^{-t/\tau'_i}\right) \quad (8)$$

176

177 with  $\tau'_i = \text{const.}$

178 The evolution due to diffusion plus gel relaxation can thus be written as:

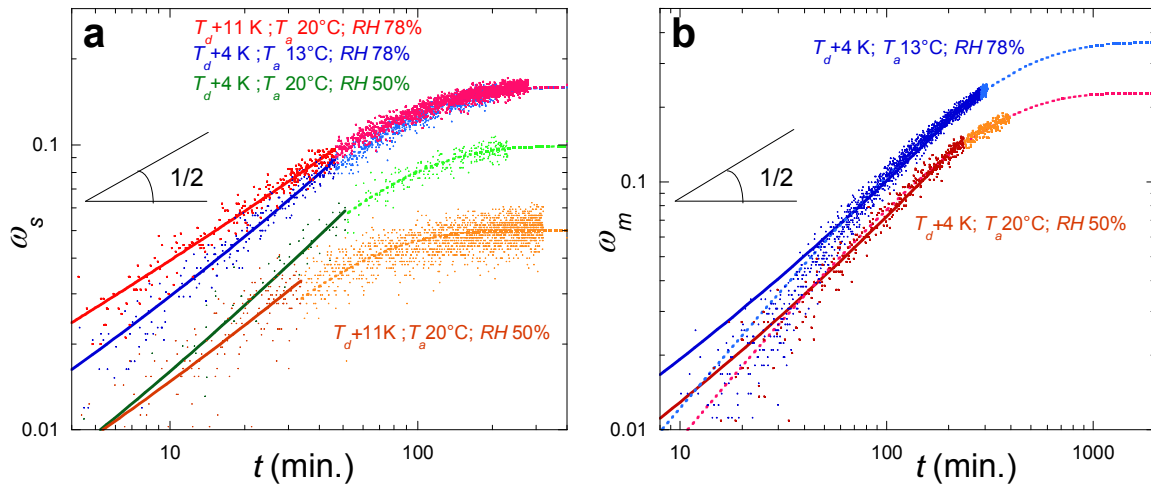
179

$$180 \quad \omega_i = \omega_{i,\infty} \left(1 - e^{-t/\tau_i}\right) + \omega'_{i,\infty} \left(1 - e^{-t/\tau'_i}\right) \quad (9)$$

181

182 In Fig. 2 are reported typical adsorption isotherms and in Table 2 the results of the fits to Eqs.  
 183 2, 3 using data in the range  $\omega_i < 0.6\omega_{i,\infty}$ . For small grains, the exponent of single power law,  
 184 Eq. 2, are found in the range  $[0.58 - 0.79]$ , with mean value 0.69 closer to 0.5 than to 1,  
 185 showing that vapor diffusion plays the major role in the relaxation process. This is  
 186 corroborated with double power law fit, Eq. 3, where the amplitude of the  $t^{1/2}$  term is about 10  
 187 times larger than the  $t$  term. For medium grains, the relaxation is too long to obtain data close

188 to saturation, then the fit to exponential decay Eq. 5 is made over all the data range, which  
 189 gives an estimation of  $\omega_{m,\infty}$ . Data are then fitted to power laws in the range  $\omega_m < 0.6\omega_{m,\infty}$ .  
 190 The results of the fit to the exponential relaxation, Eq. 5, are reported in Table 2. According to  
 191 Eq. 5, the relaxation times  $\tau_m/\tau_s \approx (R_m/R_s)^2 \approx 13.6$ . The measured ratio is smaller,  $\tau_m/\tau_s \approx$   
 192 4.88, confirming that gel relaxation also matters. Considering only water diffusion in the  
 193 polymer, one infers  $D_p \sim 10^{-11} \text{ m}^2 \cdot \text{s}^{-1}$ , a typical value in gels.  
 194 Data (Fig. 2a) show, as expected (see e.g. Delavoipière et al., 2018), that  $RH$  is the only  
 195 parameter for the adsorption amplitude  $\omega_{i,\infty}$  (see the isotherms at  $T_a = T_p = T_d + 11\text{K}$  and  $T_d$   
 196  $+ 4\text{K}$  with air at same temperature than the substrate and  $RH = 78\%$ ). Adsorption where the  
 197 plate temperature is at a temperature lower than air ( $T_p = T_d + 4\text{K}$ , air at  $T_a = 20^\circ\text{C}$  and  $RH =$   
 198  $50\%$ ) would correspond to a mean isotherm at  $RH \approx 64\%$ . Medium grains isotherms (Fig. 2b)  
 199 correspond to the last case ( $T_p = T_d + 4\text{K}$ , air at  $T_a = 20^\circ\text{C}$  and  $RH = 50\%$ ).  
 200



201  
 202  
 203 Fig. 2. Evolution of sorption isotherms ( $\omega_{i=s,m}$ , log-log plot,  $RH < 100\%$ ). The full straight  
 204 lines are power law fits to data 60% below the saturation value (Eq. 2, darker points)) and the  
 205 interrupted curves are exponential fits to data above 60% of the saturation value (Eq. 5) (see

206 Table 2). (a) Small grains. (b) Medium grains, where exponential fit is made with all data (see  
 207 text).

208

| Fitting                    | Parameter  | Small grains                      |                                  |                                   |                                  | Medium grains                          |  | Bare                             |      |
|----------------------------|--|-----------------------------------|----------------------------------|-----------------------------------|----------------------------------|--|--|----------------------------------|------|
|                            |  | 50                                | ≈ 64                             | 78                                |                                  | ≈ 64                                   | 78                                       | SR                               | 1.32 |
|                            | $RH$ (%)   | 50                                | ≈ 64                             | 78                                |                                  | ≈ 64                                   | 78                                       |                                  |      |
|                            | $T_p - T_d$ (K)  | 11                                | 4                                | 4                                 | 11                               | 4                                      | 4  |                                  |      |
|                            | $m_i$ (g)  | 9.75                              | 9.14                             | 9.20                              | 9.00                             | 7.34                                   | 7.14                                     |                                  |      |
| Single power law<br>Eq. 2  | $A_i$  | 0.0032<br>$\pm 4 \times 10^{-4}$  | 0.0026<br>$\pm 4 \times 10^{-4}$ | 0.0056<br>$\pm 2 \times 10^{-4}$  | 0.0102<br>$\pm 2 \times 10^{-4}$ | 0.0169<br>$\pm 8 \times 10^{-5}$       | 0.00257<br>$\pm 5 \times 10^{-5}$        |                                  |      |
|                            | $x$  | 0.66<br>$\pm 0.03$                | 0.79<br>$\pm 0.04$               | 0.72<br>$\pm 0.01$                | 0.58<br>$\pm 0.01$               | 0.81<br>$\pm 0.03$                     | 0.80<br>$\pm 0.03$                       |                                  |      |
| Double power law<br>Eq. 3  | $A_i$  | 0.0034<br>$\pm 4 \times 10^{-4}$  | 0.0026<br>$\pm 6 \times 10^{-4}$ | 0.00608<br>$\pm 3 \times 10^{-4}$ | 0.0109<br>$\pm 2 \times 10^{-4}$ | 0.00423<br>8<br>$\pm 6 \times 10^{-6}$ | 0.0026<br>$\pm 2 \times 10^{-4}$         |                                  |      |
|                            | $B_i$  | 0.00040<br>$\pm 8 \times 10^{-5}$ | 0.0008<br>$\pm 1 \times 10^{-4}$ | 0.00102<br>$\pm 5 \times 10^{-5}$ | 0.0048<br>$\pm 4 \times 10^{-5}$ | 0.00058<br>6<br>$\pm 9 \times 10^{-5}$ | 0.0004632<br>4<br>$\pm 1 \times 10^{-5}$ |                                  |      |
| Exponential decay<br>Eq. 5 | $\omega_{i,\infty}$                                      | 0.0499<br>$\pm 1 \times 10^{-4}$  | 0.0989<br>$\pm 7 \times 10^{-4}$ | 0.1593<br>$\pm 5 \times 10^{-4}$  | 0.1592<br>$\pm 3 \times 10^{-4}$ | 0.228<br>$\pm 2 \times 10^{-3}$        | 0.365<br>$\pm 3 \times 10^{-3}$          |                                  |      |
|                            | $\tau_i$ (min.)  | 39<br>$\pm 0.6$                   | 60<br>$\pm 1.5$                  | 64.8<br>$\pm 0.6$                 | 55.8<br>$\pm 0.4$                | 242<br>$\pm 2$                         | 294<br>$\pm 3$                           |                                  |      |
| Lin. evol.<br>Eq. 11       | $dh/dt$<br>( $\times 10^{-3}$<br>mm.min. <sup>-1</sup> ) |                                   |                                  |                                   |                                  |  |  | 1.4207<br>$\pm 2 \times 10^{-3}$ |      |

209

210

211 Table 2. Results of the fits of the adsorption data. Uncertainties: One standard deviation.

212

#### 213 4. Below the dew point

214

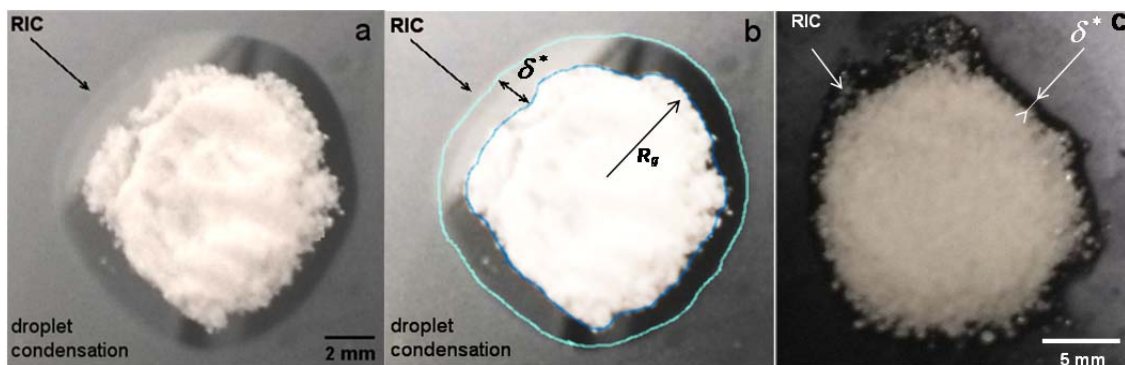
215 When the substrate temperature is set below the dew point temperature, condensation takes  
 216 place. Condensation on gels exhibits specific features when compared with condensation on a  
 217 bare surface.

218

##### 219 4.1. Region of inhibited condensation.

220

221 In Fig. 3 is shown thin ( $< 1\text{mm}$ ) layers of small and medium gel grains in a circle of radius  $R_g$   
 222  $\sim 15\text{ mm}$  on a bare Si surface at  $T_p = T_d - 6.7\text{ K}$ . Dropwise condensation is observed on the Si  
 223 surface naturally coated with an oxidation layer whose contact angle with water is  $\theta \approx 60^\circ$   
 224 (see e.g. Narhe et al., 2004).  
 225 The hygroscopic nature of the gel due to the osmotic pressure built-up by its hydrophilic sites  
 226 induces enhanced adsorption of water vapor and thus lowers vapor pressure at the gel border,  
 227 giving rise to a region of inhibited condensation (RIC) on the bare silicon substrate  
 228 surrounding the gel sample, with width  $\delta^*$  as defined in Fig. 3. This RIC is similar to the dry  
 229 region around lyophilic patches during diethylene glycol condensation (Schafle et al., 2003)  
 230 or around a salty droplet (Guadarrama-Cetina et al., 2014).  
 231 To obtain the  $\delta^*$  and  $R_g$  values shown in Fig. 4, the processing of the images includes  
 232 smoothing, contrast enhancement and border detection, which was performed by using the  
 233 Fiji® routines. Due to the irregular borders (see Fig. 3), the average distance between the gel  
 234 and the condensation pattern was determined within a small region.  
 235



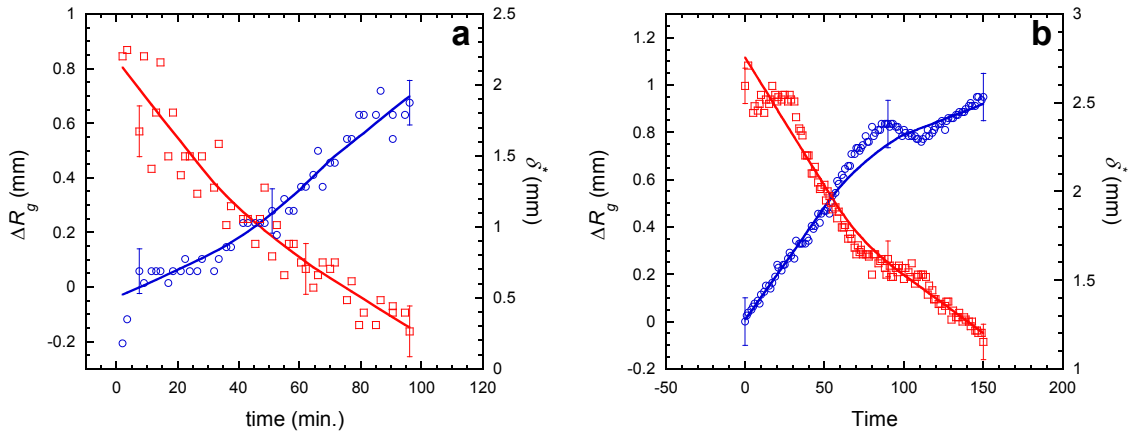
237  
 238 Fig. 3. Examples of region of inhibited condensation (RIC) around a thin ( $< 1\text{ mm}$ ) layer of  
 239 (a, b) small size grain at  $t = 25\text{ s}$ . (b) is the (a) picture with outlined gel and RIC contours. (c)  
 240 Medium size grains,  $t = 25\text{ s}$ . ( $T_a = 22\text{ }^\circ\text{C}$  at 47 % RH,  $T_p = T_d - 6.7\text{ K}$ ).  
 241

242

243 Figure 4 reports the evolution of the RIC width  $\delta^*$ , which decreases with time. This RIC  
244 decrease can be attributed to the increasing impregnation of the gel with adsorbed water.  
245 When the gel is saturated, condensation on gel proceeds with the same way as on the bare  
246 substrate, as seen in Section 4.2. The RIC width should be at that time the same as the RIC  
247 observed around each water drops or hydrophilic dots (corresponding to the lyophilic patches  
248 of Schafle et al., 2003), as a result of the surrounding water vapor gradient (see e.g. Beysens,  
249 2018). The mechanism behind the RIC evolution is thus different to what happens with a  
250 solute sample (e.g. a salty drop as in Guadarrama-Cetina et al., 2014), which comes from a  
251 reduction of saturation pressure (Raoult law) or around an ice crystal where the constant drop  
252 in saturation pressure makes the RIC width constant (Nath et al., 2018). (Further analysis is  
253 out of the scope of the present study).

254 The evolution of the gel radius increase,  $\Delta R_g = R_g(t) - R_g(0)$ , is also shown in Fig. 3. The  
255  $\Delta R_g$  growth rate decreases after about a time  $\sim 100$  s for medium grains, a value near the time  
256 where the condensation rate exhibits an inflection corresponding to the lowest influence of the  
257 adsorption process (see Fig. 5). The  $\Delta R_g$  increase is due to both adsorption and condensation  
258 processes and is proportional to the collected increasing water volume per unit surface,  $h$ ,  
259 (see Eq. 11). The prefactor is, however, difficult to precisely evaluate because it depends on  
260 the grains packing. It is clear in Fig. 4b that the rate of growth is larger at early times, as in  
261 Fig. 5. Note that the  $\Delta R_g$  behavior can be affected by the grains rearrangement during their  
262 swelling, which presumably explains the different behavior between small and medium grains  
263 and the oscillations in the  $R_g$  evolution as observed in Fig. 4b.

264



265

266

267 Fig. 4. Evolution of the RIC width  $\delta^*$  (squares) and gel radius increase  $\Delta R_g$  (circles) as  
 268 observed in Fig. 3 of (a) small grains and (b) medium grains. The curves are data smoothing.  
 269 ( $T_a = 20$  °C,  $RH = 50\%$ ,  $T_p = T_d - 4$  K).

270

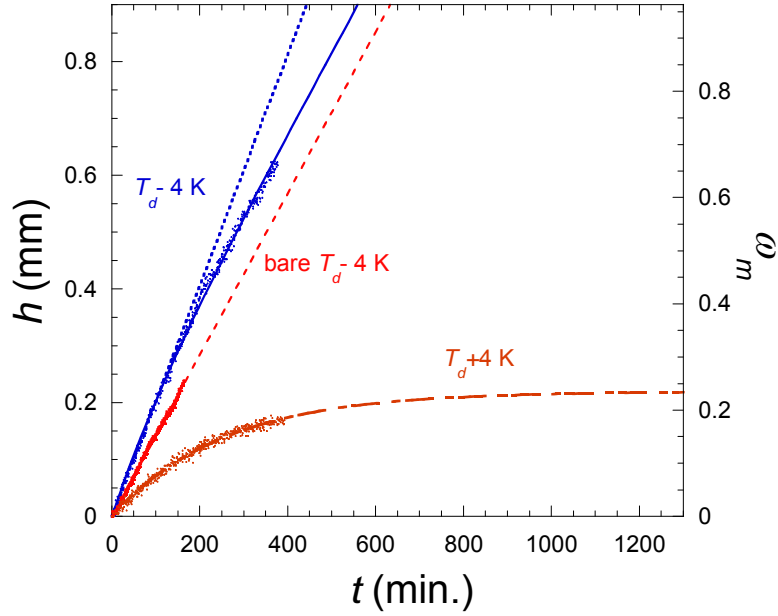
#### 271 4.2. Condensation rates

272

273 In order to compare the adsorption volume with respect to condensation on a bare substrate,  
 274 one considers the surfacic adsorbed volume or equivalent water film thickness,  $h$ . With  $\rho$  the  
 275 water density, this layer is expected to grow proportionally to time as

276

$$277 \quad h = \frac{m_w}{\rho S_c} \sim t \quad (11)$$



278

279

280 Fig. 5. Evolution of condensation ( $SR = 1.32$ ) on gel medium grains (blue dots) and bare  
 281 substrate (red dots) under same conditions ( $T_a = 20\text{ }^\circ\text{C}$ ,  $RH = 50\%$ ,  $T_p = T_d - 4\text{ K}$ ). Left  
 282 ordinate: water volume per unit projected area,  $h$ . The continuous curve is a fit of gel data to  
 283 Eq. 12 and the interrupted line is a fit of bare substrate to Eq. 11. The dotted line is the initial  
 284 slope for condensation on gel. For the sake of comparison, the sorption isotherm at  $T_a = 20$   
 285  $^\circ\text{C}$ ,  $RH = 50\%$ ,  $T_p = T_d + 4\text{ K}$  is also reported (orange dots; right ordinate; see Fig. 2b).

286

287 In Fig. 5 is reported condensation on gels and bare substrate. The bare substrate condensation  
 288 is proportional to time with slope  $(dh/dt)_b = 1.4207 \times 10^{-3} \pm 2 \times 10^{-6}\text{ mm}\cdot\text{min}^{-1}$  (uncertainty:  
 289 1 SD). Gel exhibits a larger initial rate up to time  $\approx 100\text{ min.}$  where the rate progressively  
 290 decreases to reach the bare substrate value, corresponding to condensation and imbibition of  
 291 the gel as if it were a bare substrate. The swelling ratio at which this inflection occurs ( $\sim 0.2$ )  
 292 is far less than the maximum swelling ratio of  $\sim 370$  and cannot be attributed to the vicinity of  
 293 this limit. One notes that further to this inflection the slope becomes comparable to what is  
 294 found on the bare surface. This rate decrease towards the bare substrate value can be related to

295 the corresponding decrease of the RIC width and decrease of the rate of gel radius growth,  
 296  $\Delta R_g$ , which occurs during the same time period, and which corresponds to the approach of the  
 297 saturation of adsorption. In order to assess this point, the gel data have been fitted to the sum  
 298 of condensation as if the gel were a bare substrate, Eq. 11 and the adsorption evolution, in  
 299 volume per unit surface as in Eq. 11:

300

$$301 \quad h = \left(\frac{dh}{dt}\right)_b t + h_{m,\infty}(1 - e^{-t/\tau_m}) \quad (12)$$

302

303 From Table 2, the amplitude value of the adsorption data at  $T_d + 4K$  can be expressed in  
 304 volume per projected gel surface area,  $h_{m,\infty} = \omega_{i,\infty} m_i / S_c = (0.201 \pm 0.002)$  mm. Figure 5  
 305 reports the condensation data on gel and bare substrate at  $T_d - 4K$  and the adsorption data at  
 306  $T_d + 4K$ . Gel condensation data are fitted to Eq. 12 with  $(dh/dt)_b$  free and imposed. The results  
 307 are listed in Table 3. When all parameters are left free,  $(dh/dt)_b$  is found somewhat smaller  
 308 than on the bare substrate, presumably because of the lack of data at very long times. The  
 309 adsorption time is found somewhat lower (195 s) than at  $T_d + 4K$  (300 s). The amplitude (0.24  
 310 mm) compares relatively well with what is expected (0.207 mm). With  $(dh/dt)_b$  imposed, the  
 311 typical adsorption time is 3 time smaller than expected and the adsorption amplitude is too  
 312 small (0.106 mm). When the adsorption time is fixed at the value at  $T_d + 4K$  ( $\approx 300$  s), the  
 313 amplitude (0.165 mm) increases but still remains smaller than the value at  $T_d + 4K$ . With the  
 314 latter amplitude imposed at 0.207 mm the adsorption time (391 s) becomes closer to the time  
 315 at  $T_d + 4K$  (300 s), with however a  $\chi^2$  somewhat larger than the two previous fits. (A more  
 316 detailed analysis would need more data and is out of the scope of the present study).

317



| $\chi^2$ | <i>Parameters</i> | $(dh/dt)_b$<br>( <i>mm.min.<sup>-1</sup></i> ) | $h_{m,\infty}$<br>( <i>mm</i> ) | $\tau_m$<br>( <i>min.</i> ) |
|----------|-------------------|--|---------------------------------|-----------------------------|
| 0.070    |                   | $(1.1 \pm 0.1) \times 10^{-3}$                 | $0.24 \pm 0.05$                 | $195 \pm 31$                |
| 0.054    |                   | $(1.4207 \times 10^{-3})$                      | $0.106 \pm 0.001$               | $115 \pm 4$                 |
| 0.082    |                   | $(1.4207 \times 10^{-3})$                      | $0.165 \pm 0.001$               | (300)                       |
| 0.15     |                   | $(1.4207 \times 10^{-3})$                      | (0.201)                         | $391 \pm 5$                 |

318

319

320 Table 3. Results of the fit to Eq. 11 of condensation data on gel (Fig. 5). The values under  
321 brackets are imposed in the fit. The gel mass is  $m_m = 6.94$  g. Notations: see text.

322

323 It thus results a net increase of water absorbed on gel when compared to the bare substrate  
324 under same conditions, with value on the order of 0.1 mm. This behavior can be explained by  
325 the fact that two phenomena are present: (i) an initial adsorption of water vapor, giving a  
326 vapor concentration gradient above the surface of the gel larger than on the bare substrate, at  
327 the origin of a RIC, followed by (ii) a steady condensation with the same concentration  
328 gradient as found above the water drops on the bare substrate. Water will continue to  
329 condense on the gel until it reaches its maximum swelling. As a result of the initial large  
330 water absorption rate, water absorbed by the gel is thus found in greater amount than water  
331 condensed on the bare plate.

332 Note that if instead of gel particles, one considers a gel film, one should obtain similar  
333 enhancement as the adsorption phenomenon is not due to the macroscopic shape of the gel but  
334 to the intrinsic properties of the polymer network. A gel film will then equally serve to  
335 condense water vapor and the swelling mechanism due to adsorption plus condensation will  
336 be the same. The only difference would be the value of the exposed area to condensation,  
337 which is smaller, then the condensation rate will be lower. The maximum swelling volume  
338 capacity, proportional to the gel volume, will also be smaller. As a matter of fact, such gel  
339 film condensation has already been reported by Delavoipière et al., 2018. On the other hand,

340 if there were any non-water vapor absorbing hydrophilic powder on the surface instead of the  
341 gel particles, one would simply expect no adsorption. Only filmwise condensation will occur  
342 (coefficient  $h_{m,\infty} = 0$  in Eq. 12).

343

## 344 **5. Concluding Remarks**

345

346 Common hydrogels grains used for soil in agriculture (Aquasorb 3005<sup>TM</sup>) can collect water  
347 even for relative humidity less than 100%. They also exhibit interesting properties when used  
348 in supersaturation conditions (conditions of dew formation) since they collect more water than  
349 a bare hydrophobic substrate with same projected surface area. The measured gain is on order  
350 0.1 mm of water / day, which is an important gain when compared to the current values found  
351 for dew yield (0.1 - 0.6 mm/day). This enhanced condensation of water is due to the initial  
352 water vapor adsorption, which adds to condensation. As noted in the introduction, such  
353 condensed water stored in gels can be either used in agriculture where the osmotic pressure  
354 exerted by the roots is sufficiently high to extract water or removed by moderate (~ 1 bar)  
355 mechanical pressure for human use (Milimouk et al., 2001). Another way is to evaporate  
356 water and condense it in e.g. a solar still (see e.g. Zhao et al., 2019 where details on needed  
357 energy and time duration are given). Although the use is one and only in agriculture where the  
358 grains are definitely mixed with the soil, water extraction by pressure or evaporation has to be  
359 cyclically repeated. There is, however, a possible limitation to the number of cycles due to the  
360 absorption of CO<sub>2</sub> gas from the atmosphere. HCO<sub>3</sub><sup>-</sup> ions are indeed added in the solutions,  
361 screening the polymer charges and thus progressively reducing the swelling amplitude (see  
362 e.g. Rička and Tanaka, 1984 for ions influence). Precise evaluations remain to be carried out.

363 In addition, although the above study has been performed in laboratory by contact cooling,  
364 preliminary experiments under outdoor radiative cooling (Beysens, 1998) give, at least

365 qualitatively, the same results. Emissivity of dry gels is indeed high, as in any organic  
366 materials and, when wet, their emissivity becomes close to pure water emissivity (0.98; Schott  
367 et al., 2001). Outdoor radiative condensation unsurprisingly exhibits the same properties and  
368 constraints than condensation on a solid substrate (e.g. clear sky, high nocturnal relative  
369 humidity, low wind speed, water evaporation under direct sun light; see Beysens, 2018).  
370 Further research will be needed to get a Proof of Concept, but these results are already very  
371 encouraging in view of the development of new materials to enhance dew water collection.

372

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374

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378

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