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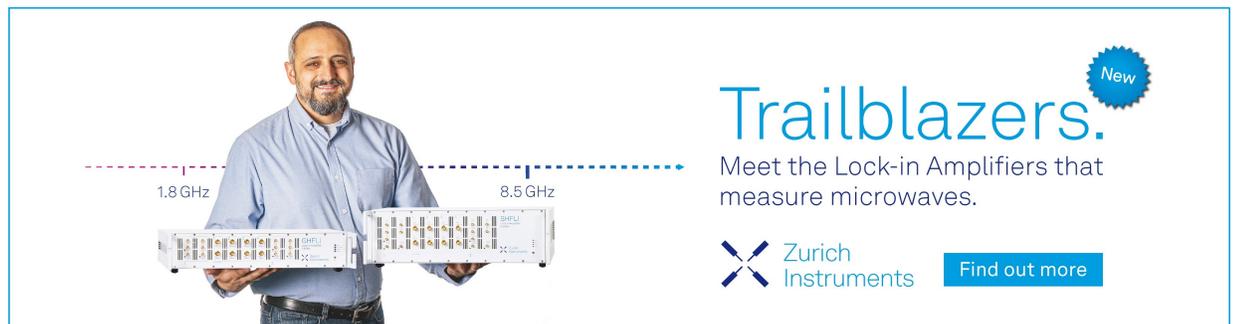
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# Humidity Characterization and Control in Planar Micro-Tracking CPV Modules

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**Abstract.** To better understand the process of condensation formation in CPV modules, an experimental setup containing two Insolight mockup modules has been prepared to firstly, monitor the relevant variables involved in the internal dew point, namely the internal relative humidity and air temperature, the differential atmospheric pressure between the module and the environment and the temperatures of the front and rear parts of the modules, and secondly, to be able to modify the exchange conditions with the environment. After spending the wet season in Madrid (four months during the winter), the formation of condensation has been correlated with the monitored dew point and most of the time it disappears after a few hours. Considering that sealing the module would increase the internal pressure to the point of failure due to thermal expansion, the modules are always equalized through a breather. Hence, some preliminary mitigating actions have been studied such as the addition of desiccant and different venting configurations that seek to reduce the amount of humidity content and therefore help prevent the formation of the dew point.

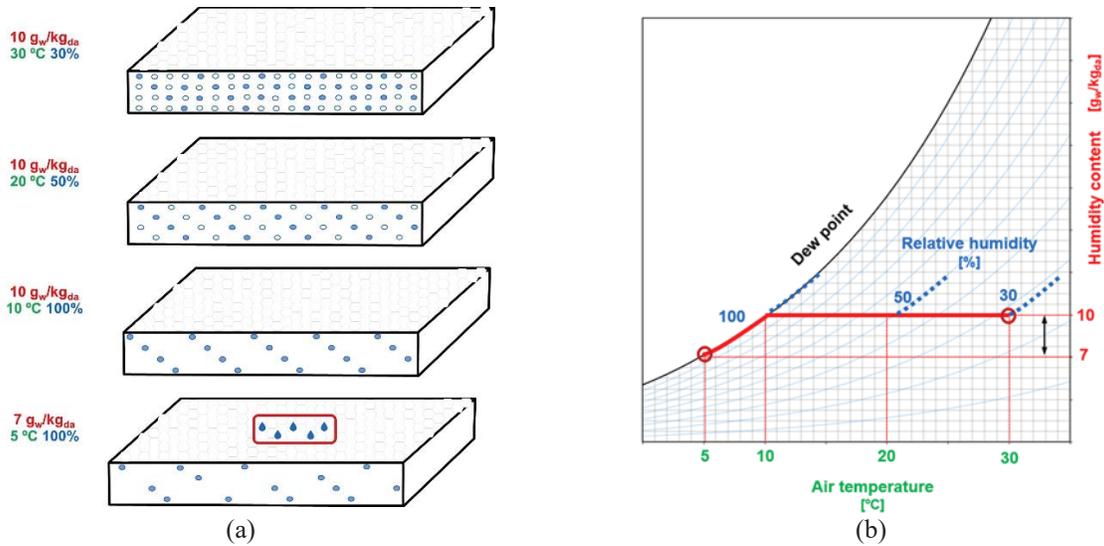
## INTRODUCTION

Moisture content in CPV modules is a relevant parameter to consider, especially related to the long-term performance of the components, as water vapor and condensed water may affect reliability [1,2]. In addition, condensation usually occurs on the front face of the module where primary optics are placed, which reduces their transmittance and concentration capacity, seriously affecting performance.

A convenient methodology for plotting humidity content in air is to represent it on the psychrometric chart, a graphical representation of the equation of state of air humidity (see Fig.1b). The relationship between humidity content (measured in grams of water per kg of dry air) and air temperature is related to a specific relative humidity value. In this context, the hundred percent line shows the saturation limit of the air at a given temperature, the dew point, the moment at which condensation occurs.

A descriptive example with a rough calculation is presented in Fig. 1 considering a CPV module with a fixed amount of moisture content: ten grams of water vapor per kilogram of dry air, so at 30 degrees this means 30% of relative humidity. As the air temperature decreases, the relative humidity increases until finally the dew point is reached for that level of moisture content, 10 °C in this example. At this point, any reduction in air temperature is going to result in condensation of some portion of the moisture in the air.

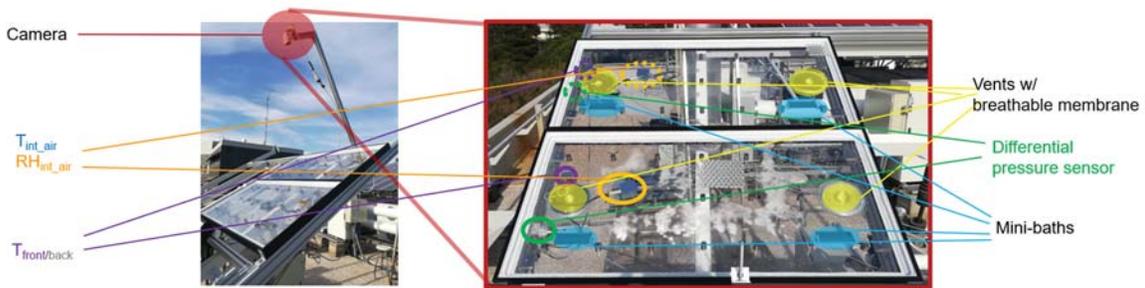
In the case of CPV modules, the lenses, being exposed to the sky, are the coldest part due to radiative cooling and where dew forms first.



**FIGURE 1.** Descriptive process of condensation formation due to dew point reach by lowering air temperature (a) shows schema representing the level of humidity (b) shows the process in a psychrometric chart.

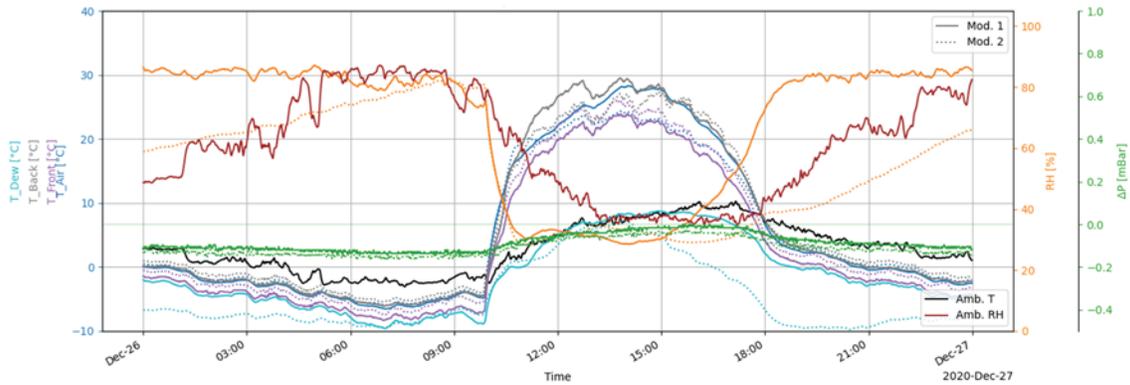
## Experimental Set-Up

To better understand the condensation formation process, an experimental set-up has been prepared at IES-UPM containing two Insolight modules to control the relevant variables involved in the internal dew point. The description of the Insolight module can be founded in [3,4]. The mockups are dummy modules, with the same dimensions and materials as a module, but without PV cells and only a limited area covered with lenses. For the sake of simplicity, the means for the internal tracker have not been included in these first modules. These mockups are equipped with sensors to monitor the internal relative humidity and air temperature, the differential atmospheric pressure between the module and the environment and the temperatures of the front and rear sides of the modules. In addition, the mockups can be tuned to modify the conditions of exchange with the environment by means of two ventilation ports placed at the backplane that can be either completely sealed or coupled with Gore membranes or labyrinth breather valves to equalize the pressure with the environment. In addition, mini-baths have been added inside the modules to add a controlled amount of water to force air saturation inside the module. A camera has been installed over the modules to obtain pictures on how dew is being formed/decreased. Figure 1 shows photographs of the set-up.



**FIGURE 2.** Photographs of the experiment containing two Insolight mockup modules and several sensors to monitor the humidity levels inside.

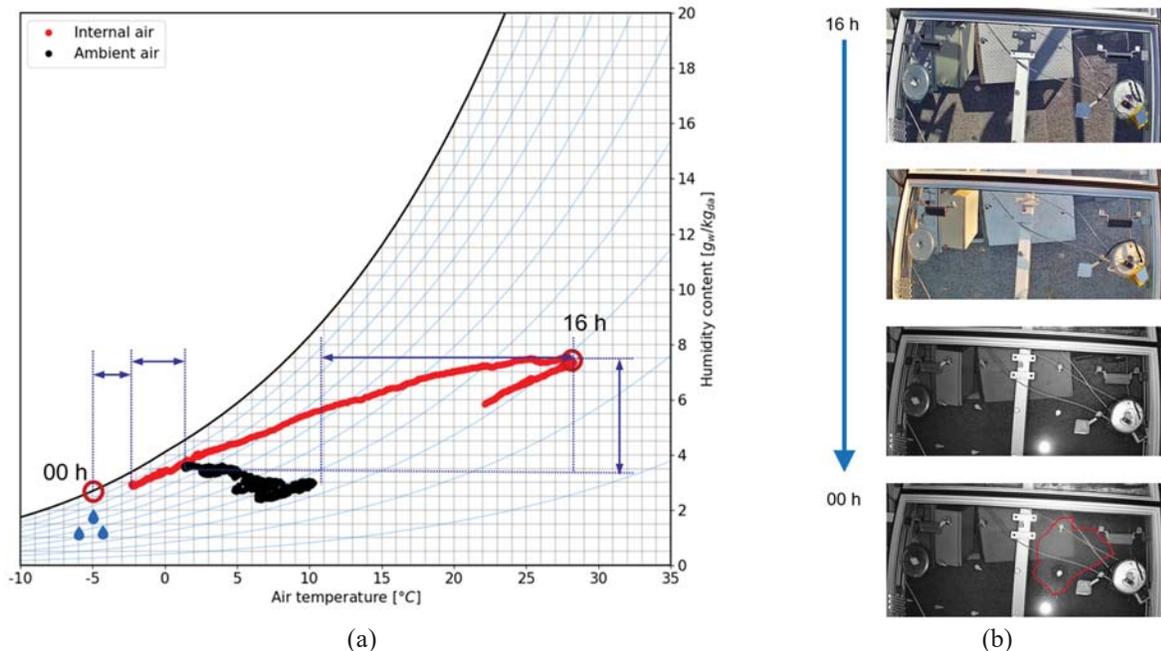
The temporal evolution of the monitored variables plus the expected dew point derived from the measurements in the two modules, both with Gore membranes is shown in Figure 3. The differences between the relative humidity and dew points of the modules are due to the forced addition of water in Module 1 during an experiment explained below in “Ventilation” section.



**FIGURE 3.** Evolution over one day of the monitored variables of the experimental setup of the two modules simulated with the same ventilators, two Gore membranes. The differences between the relative humidity and dew points of the modules are due to the addition of water in module 1 to achieve forced condensation. The details of this experiment are explained later in the "Ventilation" section.

### FORMATION OF CONDENSATION

The example showing condensation formation detailed in the "Introduction" can be reproduced with this setup and is presented in Fig 4a. The ambient humidity content can be seen in black with a thermal excursion of 10 °C typical of winter in Madrid and the corresponding evolution of the air inside the module in red once the maximum temperature is reached by 16 h. At this moment, the air is cooling down so the relative humidity increases approaching the dew point. Although the module is equalized in pressure, the ambient and internal air have different slope due to the desorption that occurs in the internal materials, solar irradiation during the day and radiative cooling from the sky during the night. During clear sky conditions in the night, sky temperature is much lower than ground temperature, so radiative cooling causes that the front side is the coldest part of the module so condensation will occur here first.

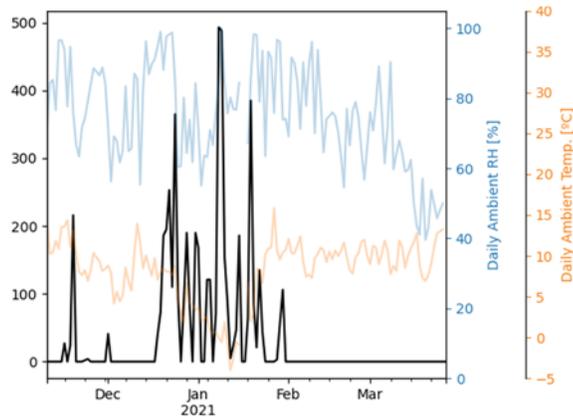


**FIGURE 4.** Condensation formation (a) Psychrometric chart with the daily evolution of ambient and mockup module humidity content (b) photographs of the time evolution in the mockup module showing the condensation formation.

## Formation of Condensation in Madrid Conditions

To account for the condensation probability in the mockups in Madrid, we will consider the following metric: the number of times per day when the dew point condition is reached. Figure 5 shows that daily period, in minutes, during the four winter months when the experiment was carried out. Dew formation was also confirmed by visual inspection with the camera, crossing dew point formation frequency with photographs confirmed a clear correlation. For this mockup configuration with two vents (75 mm diameter from Gore) placed on the ventilation ports, condensation dries up in the first minutes after sun rise in the typical sunny and dry days of winter of Madrid, while it may take a few hours in the humid days.

At the same time, in a second mockup module, additional humidity was introduced in the baths, thus forcing immediate condensation. Since there was 10 to 20 times more humidity present than in natural conditions, it takes much longer for the ventilation to get rid of the condensation. This experiment will be discussed in detail later.



**FIGURE 5.** Number of times per day that condensation forms considering minute sampling plus daily ambient relative humidity and air temperature.

## CONDENSATION REDUCTION/PREVENTION

To prevent/reduce condensation different strategies can be considered. Sealing the module would increase the internal pressure at specific operating conditions, which may reach the point of failure due to thermal expansion. Consequently, for the sake of reliability, the module must be equalized with the ambient pressure with breathers. Thus, the internal humidity content will follow the ambient conditions, with certain time delay.

In order to minimize the events of condensation inside the module, the inner air humidity must be decreased to prevent dew point. One way could be to increase the module temperature during the night, a non-passive solution that would require a significant power consumption. A better possibility to reduce the humidity content is by means of desiccants or ventilation with dry air before the dew point is reached; this is the method normally used in CPV modules [5-7].

### Desiccants

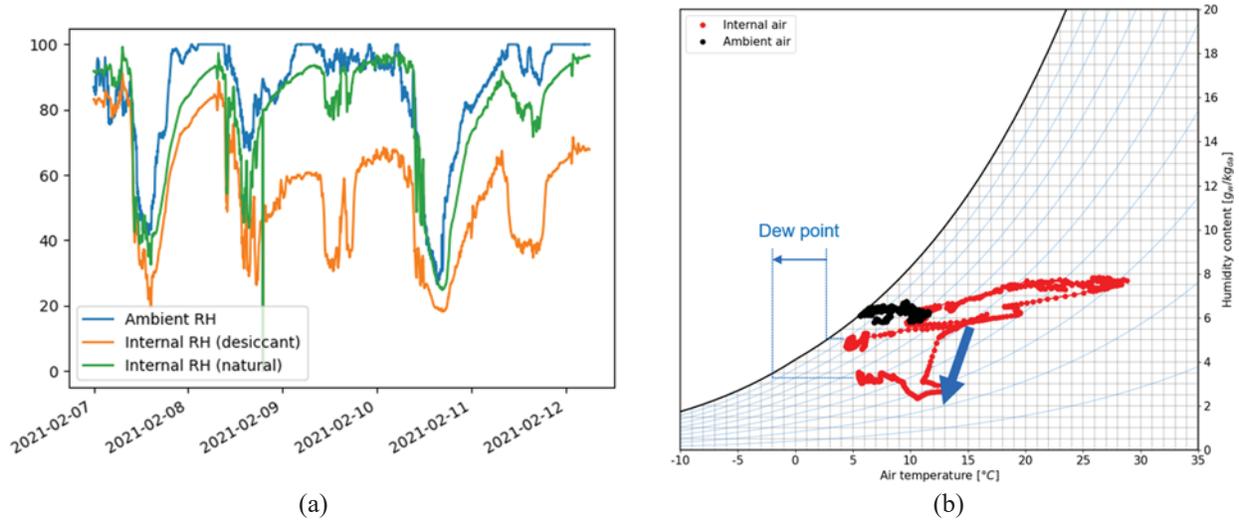
Desiccants such as silica gel, molecular sieves or clays are hygroscopic materials, that is, materials that can adsorb vapor molecules on their surfaces. They can be understood as “moisture sponges”, each type having a specific moisture sorption isotherm, but having in common that they all adsorb more moisture as the relative humidity level increases. This behavior allows them to be used as moisture dampers, so desiccants can act as buffers for moisture variation and operating conditions move away from the condensing condition.

The exact amount of desiccant to set a humidity point will depend on parameters such as moisture content, volume, desiccant type, and air exchange rate between the module and the ambient.

## Desiccant Performance

Ten grams of silica gel was added to the experimental module in the upper left corner, next to the window opening (called desiccant in Fig. 6, in orange) while the other module was left in natural conditions without desiccant (green in Fig. 6). After a few hours, the relative humidity is clearly reduced and maintained for several days, thus avoiding the risk of condensation.

The insertion of the silica gel reduces the humidity content inside the module so that the dew point is shifted to lower levels as can be clearly detected in the psychrometric chart. However, since the modules work with breathing membranes, high air exchange rates are expected, and long-term monitoring is underway to check both efficiency and reliability.

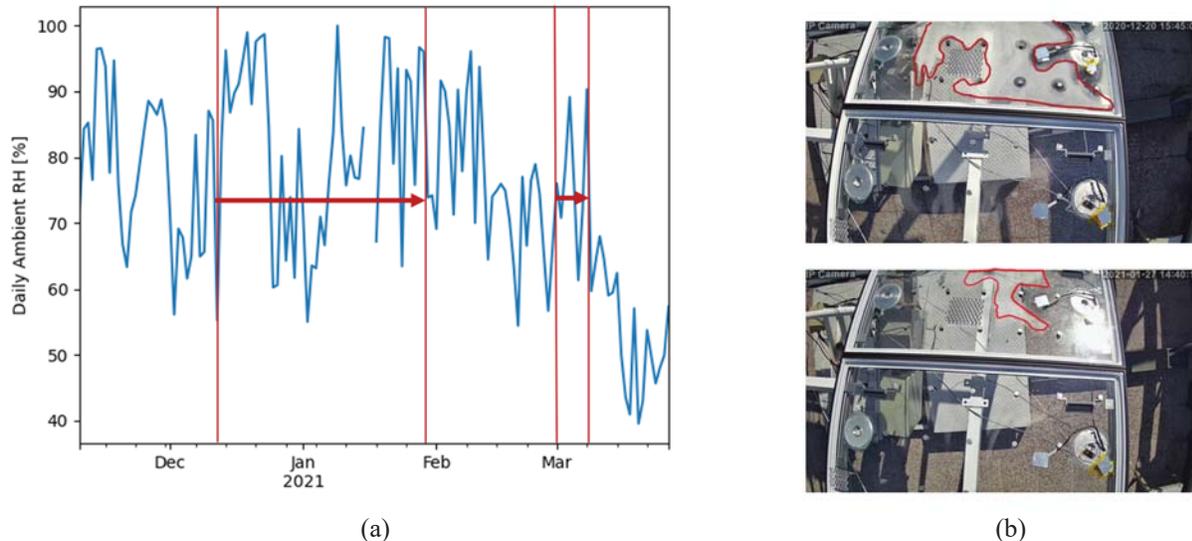


**FIGURE 6.** Effect of desiccant insertion into module (a) relative humidity level of ambient, internal of module with desiccant and internal of module at natural conditions (with no desiccant) (b) psychrometric chart showing ambient humidity content and internal humidity in module with desiccant. Ten grams of silica gel was added to the experimental module (orange in (a)) while the other module was left in natural conditions without desiccant (green in (a)). After a few hours, the relative humidity is clearly reduced and maintained for several days, thus avoiding the risk of condensation.

## Ventilation

An alternative to eliminate condensation, once it occurs, is a correct ventilation. The internal tracking of the Insolight module can significantly change the inner volume of the module, and consequently can be programmed to cause forced ventilation in the module to contribute to the humidity control. The mockup modules do not have the means for the tracker, so they are not prepared to accomplish this task so far. We have carried out preliminary studies of the ventilation effect and how it speeds up the condensation removal with the current mockup modules, taking advantage of the ventilation ports.

As explained above, due to the natural conditions in Madrid, condensation disappears within a few hours only with the help of the Gore membranes. Hence, in this experiment, the humidity content has been forced by adding water so that there is ten to twenty times more humidity forcing immediate condensation. Given the high moisture content inside the module and the wet Madrid winter, it took more than a month to finally dry through the two Gore membranes (first period showed in Fig. 7a).



**FIGURE 7.** Module drying time under forced condensation conditions. Two drying processes are shown, indicating the time when water was added and the time when it was visually decided that the module was free of condensation (a) Two drying experiments are shown together with the daily ambient relative humidity. (b) Initial (up) and after several weeks (down) photographs of the first experiment of the module under forced condensation conditions.

The experiment was repeated (second period showed in Fig. 7a), this time adding half as much water, five milliliters, but again much more dew is formed than the temperature and air volume can handle. So once more, condensation forms within a few hours, but this time with better drying conditions, in ten days almost all condensation has disappeared. To force ventilation, the two windows were opened and within a few hours the remaining condensation disappeared.

After these preliminary experiments it can be determined that ventilation acts by accelerating the transfer of water from the module to the ambient. Therefore, breather should improve the air exchange rate primarily by increasing the window exchange area, reducing the pressure drop of the breather (in addition to Gore membranes, labyrinth filters can be considered), trying to take advantage of the stack effect by considering pressure changes due to temperature differences and in the case of modules with an internal tracking, it can be used to achieve forced ventilation during non-operating time with a negligible energy consumption.

## CONCLUSION

A complete experimental setup has been prepared to monitor and control humidity. In terms of humidity inspection, once condensation forms, the experiments showed that air monitoring is not sufficient and visual inspection is required.

Dew point and condensation monitoring experiments carried out with Insolight mockup modules demonstrated that, in the winter of Madrid, modules are hardly affected by condensation when modules are equipped with Gore membranes for breathing and equalizing pressure to ambient. However, in real CPV modules with lenses and cells baseplate a higher air temperature is expected so a lower level of humidity and dew point would be reached.

As for desiccants, we have proved that very small quantities are enough to function as moisture "buffers", capable to move away from the dew point and prevent inner condensation. Further long-term monitoring is necessary to validate their performance and reliability.

Ventilation is key to eliminating condensation. The integration of breathing components in the module such as Gore vents or labyrinth valves together with the volume variation caused by the internal tracking would be a complementary capability to promote ventilation and remove condensation with minimum energy consumption. This is a unique ability supported by the internal tracking of Insolight module, capable of changing the interior volume by a factor of two.

## ACKNOWLEDGMENTS

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