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To cite this article: F Frasca *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **364** 012093

IOP Conf. Series: Materials Science and Engineering **364** (2018) 012093 doi:10.1088/1757-899X/364/1/012093

The capability of capacitive sensors in the monitoring relative humidity in hypogeum environments

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Abstract. Hypogeum environments are characterized by high levels of relative humidity (RH). Most humidity sensors currently in use are based on the capacitive effect of the dielectric material to change according to water vapour uptake. In hypogeum environments the dielectric material can be saturated by water vapor, implying a significant error in the RH measurement. To improve the capacity of this type of humidity sensors, a modified hygrometer capacitive sensor, which uses a heating cycle to avoid the condensation, has been recently developed by Rotronic®. During four field campaigns in two different hypogea environments (the Monkey Tomb in Siena and the Mithreum of Caracalla Baths in Rome), RH was measured using the conventional capacitive sensor (CCS) and the heated capacitive sensor (HCS). The purpose of this study was to investigate the capability of HCS to detect RH variations when the environmental conditions were close to vapor saturation. Significant differences were found between the measurements of the two sensors: when RH was close to 100%, the CCS was not able to detect the RH decrease, giving only a measure of RH=100%, while HCS detected such a RH decrease. Therefore, these results encourage the use of HCS in the monitoring of RH levels in extreme humidity sites such as hypogea sites.

1. Introduction

Hypogea, usually located in subterranean structures, are characterized by specific thermo-hygrometric conditions [1-2]: the temperature (T) has low daily and seasonal fluctuations and rarely exceeds 20°C, whereas the relative humidity (RH) is always over 90%. This implies that such environment is often close to vapor saturation [3]. The presence of liquid water on the stone surface and inside the material can induce chemical reactions such as salt crystallization/dissolution or biological colonization. These dynamic processes are influenced by daily cycles of RH [4], with an increase or decrease of deterioration related to the RH range. Therefore, the microclimate monitoring within hypogea sites, plays a key role in the preventive conservation of the artifacts contained therein.

Most of humidity sensors currently in use [5] are based on the capacitive effect of the dielectric material to change according to the water vapor uptake. The main disadvantage of the capacitive sensor is that it is strongly affected by the saturation of the dielectric material, introducing a significant error in the measurement. When the environment is close to saturation (RH=100%), the sensor hardly detects any further RH decrease and hence there is a lack of information on the RH behavior.

To improve the capacity of this type of humidity sensor, Rotronic® has integrated a heater in the conventional capacitive sensor (CCS) to prevent the saturation of the dielectric material. This modified capacitive sensor is generally defined as the heated capacitive sensor (hereafter called HCS). Some tests have demonstrated that, if the CCS sensor exposed to 100% RH, employs for example 4 hours to reach saturation, when exposed to a lower value of RH (95%) double of the time, i.e. 8 hours, is necessary to detect the RH decrease.

The aim of this study is to investigate the capability of HCS with respect to the conventional capacitive sensor, to detect RH variations when the environmental conditions are close to vapor saturation. Both sensors were installed in two hypogea heritage sites: The Monkey Tomb in Chiusi (Siena, Tuscany) and the Mithraeum within the Caracalla Baths in Rome. The hypogea sites considered in this study do not have the same architectural characteristics: The Monkey Tomb (Figure 1) is totally closed, no openings except for the main entrance; the Mithraeum of the Caracalla Baths (Figure 2) has the main entrance on the North side, and a big arch on the South side connected to the outdoors.

In this study, RH data measured using the HCS and the CCS were compared to investigate to which extent the HCS is more effective than the CCS.

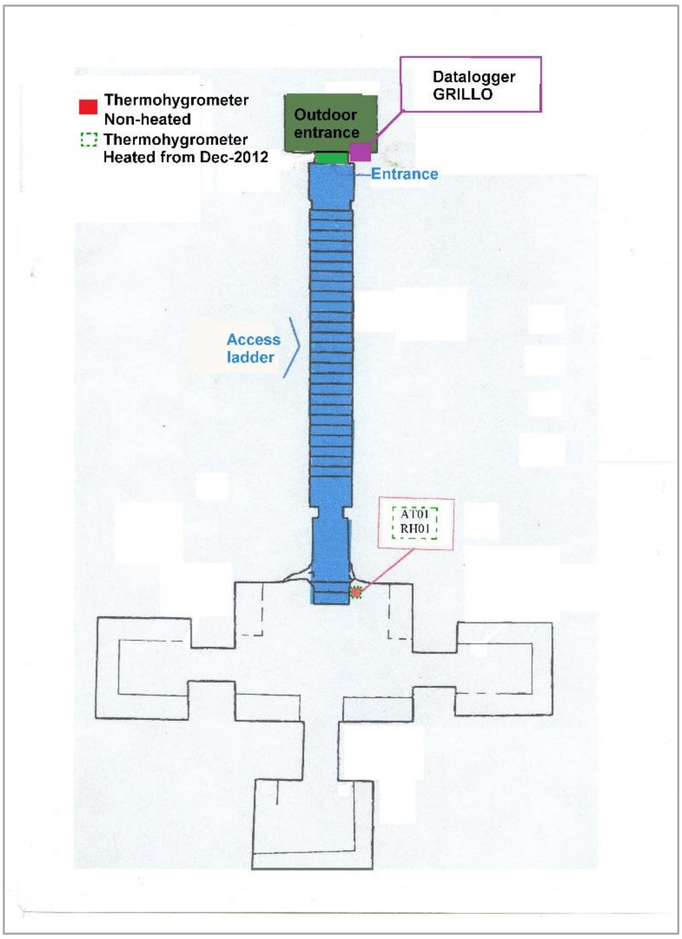

Figure 1. Plan of the Monkey Tomb in Chiusi (Siena, Tuscany), indicating the sensors installed. The thermo-hygrometer is indicated as AT01-RH01. Composed by the CCS in the first campaign and replaced by the HCS on 12 December 2012.

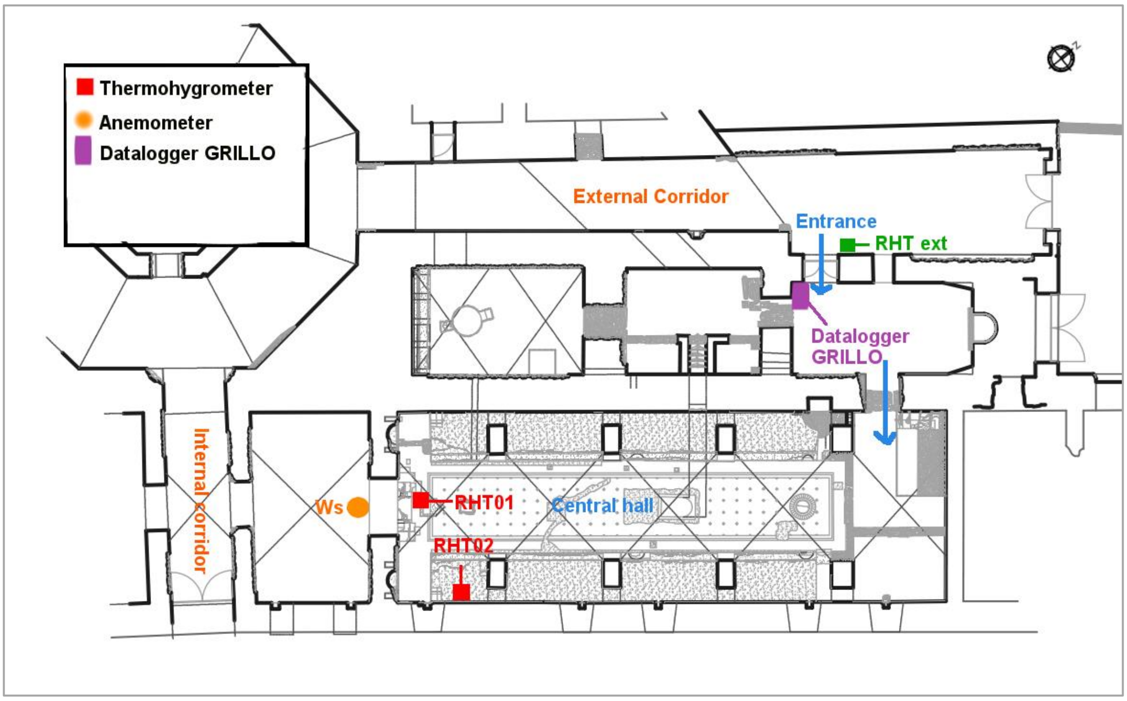

Figure 2. Plan of the Mithraeum of the Caracalla Baths in Rome, with the installed sensors. The indoor thermo-hygrometers (indicated as RHT01 and RHT02) used the CCS, replaced by the heated type on 11 November 2015. Ws indicates the biaxial sonic anemometer. RHT ext is the thermo-hygrometer installed outdoors.

2. Materials and methods

The microclimate monitoring on both sites was carried out using two electronic thermo-hygrometers developed and distributed by Rotronic®: the thermo-hygrometer model with the conventional capacitive sensor (CCS) and the heated capacitive sensor (HCS). The temperature is always measured by a platinum resistance sensor (Pt100), whereas for RH the same type of the capacitive sensor is used, but in the HCS a heater is installed under the capacitive sensor to prevent the dielectric saturation in environments with very high RH.

Two field campaigns were carried out for each heritage site: the first campaign using the CCS sensor, the second using the HCS sensor. Table 1 summarizes monitoring periods for each site. *In this study, the sensors have not been contemporaneously used in the identical period. In fact, we have assumed that in hypogeum environments the thermo-hygrometric conditions are very stable over a year, so that the comparison can be significantly carried out also taking into account the same time interval in different years. It should be noticed that the two sensors have been tested in a climatic chamber under the same thermo-hygrometric conditions to test their response time, before performing the field campaigns.*

Table 1. Duration of the two microclimate monitoring campaigns carried out with non-heated (CCS) and heated (HCS) sensors, for each site.

Hypogeum site	Period of monitoring	
	CCS	HCS
Monkey Tomb	22 September 2011 –11 December 201	12 December 2012 -27 February 2013 6 July 2016 – 17 June 2017
Mithraeum of Caracalla Baths	12 November 2013 – 27 July 2014	12 Nov 2015 – 27 April 2017

Table 2 summarizes the sensors' technical characteristics. The HCS internal working cycle consists of three phases: measuring - heating - waiting (before undertaking further measurements). The working cycle lasts 6 min: 1 min for measuring, 1 min for heating and 4 min for waiting, in order not to undertake the measuring just after heating. During the heating phase the sensor needs electrical supply. The output analog signal is updated during the measuring phase and remains constant for the other two phases.

All sensors were connected to the GRILLO MMTS datalogger, developed and distributed by Tecno.El s.r.l., with remote data transmission by GSM/GPRS technology (Global System for Mobile Communications/General Packet Radio System). Data are transmitted to the server allowing their visualization and download. For these studies, the acquisition time is set to 5 minutes and the processing time is set to 30 minutes, providing the minimum, maximum and the average of the recorded parameters.

Table 2. Technical characteristics of CCS and HCS Rotronic® sensors.

CCS	Physical variable	Accuracy
Thermo-hygrometer: Platinum resistance Sensor (PT 100)	Air temperature (T °C)	± 0.3 °C
Thermo-hygrometer: Capacitive hygrometer	Relative humidity (RH %)	± 1.5%
HCS	Physical variable	Accuracy
Thermo-hygrometer: Platinum resistance Sensor (PT 100)	Air temperature (T °C)	± 0.15 °C
Thermo-hygrometer: Capacitive hygrometer	Relative humidity (RH %)	± 1.3%

In the Monkey Tomb (Figure 1), the thermo-hygrometer CCS (indicated as AT01 - RH01), was installed in the main chamber and was later replaced by the HCS on 12 December 2012. In this study these data were considered in order to compare RH measurements carried out by both heated and non-heated sensors.

In the Mithraeum of Caracalla (Figure 2), two indoor thermo-hygrometers were installed: one at 1 cm from the wall (indicated as RHT02) and one in the central hall (indicated as RHT01). In addition, an outdoor thermo-hygrometer (indicated as RHT ext) was placed in the main entrance. A biaxial sonic anemometer (indicated as Ws), was installed in the adjacent room in communication with the central hall, in order to evaluate the influence of the air flows speed (accuracy of ±2% within the measurement range) and direction (accuracy of ±3°) on the RH behaviors.

3. Results

3.1. The Monkey Tomb

The RH data collected during the two monitoring campaigns show different trends.

In Figure 3(a), no fluctuations were observed and RH was always equal to 100% from September 2011 up to the beginning of December 2012. When the CCS was replaced by the HCS on 12 December 2012, RH values decreased to 96% and fluctuated until February 2013.

Figure 3(b) showed RH measurements by HCS. The variations were detected however the values were always higher than 94%.

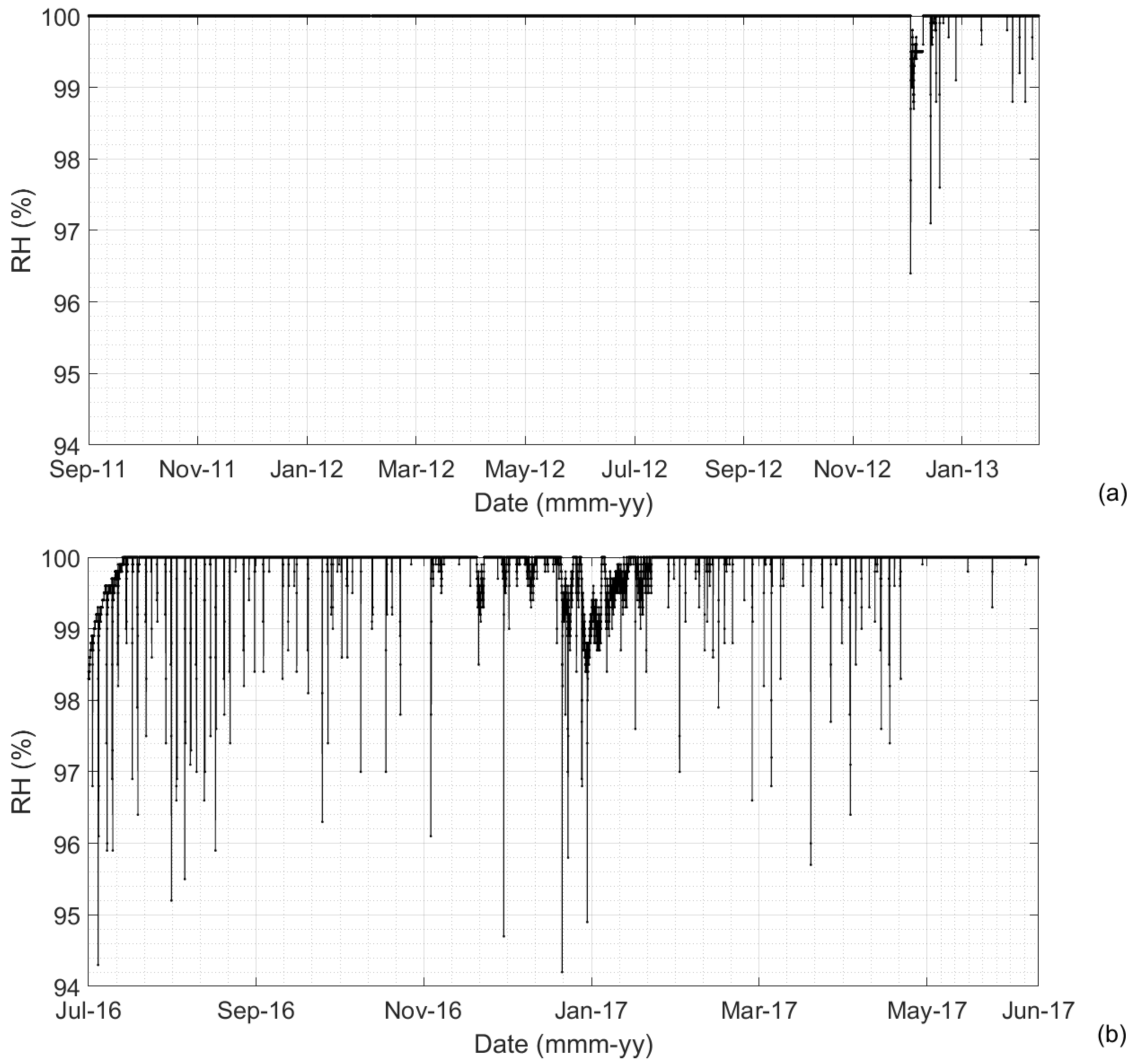

Figure 3. (a) Upper panel. RH trend in the Monkey Tomb during the period of 22 September 2011 - 27 February 2013. Measurements were carried out with CCS up to 11 December 2012, when CCS was replaced by HCS. (b) Lower panel. RH trend in the Monkey Tomb during the period of 16 July 2016 - 7 September 2017. Measurements were carried out only with the HCS.

3.2. The Mithraeum of the Caracalla Baths in Rome

The RH measurements, taken during the monitoring campaigns using CCS (Figure 4, upper panel) and HCS (Figure 4, lower panel) showed some differences.

In Figure 4 (upper panel) most values were over 90% and in few cases were below 70%, with a minimum value of 67%.

In Figure 4 (lower panel) most values were over 80% and in few cases were below 50%, with a minimum value of 31%.

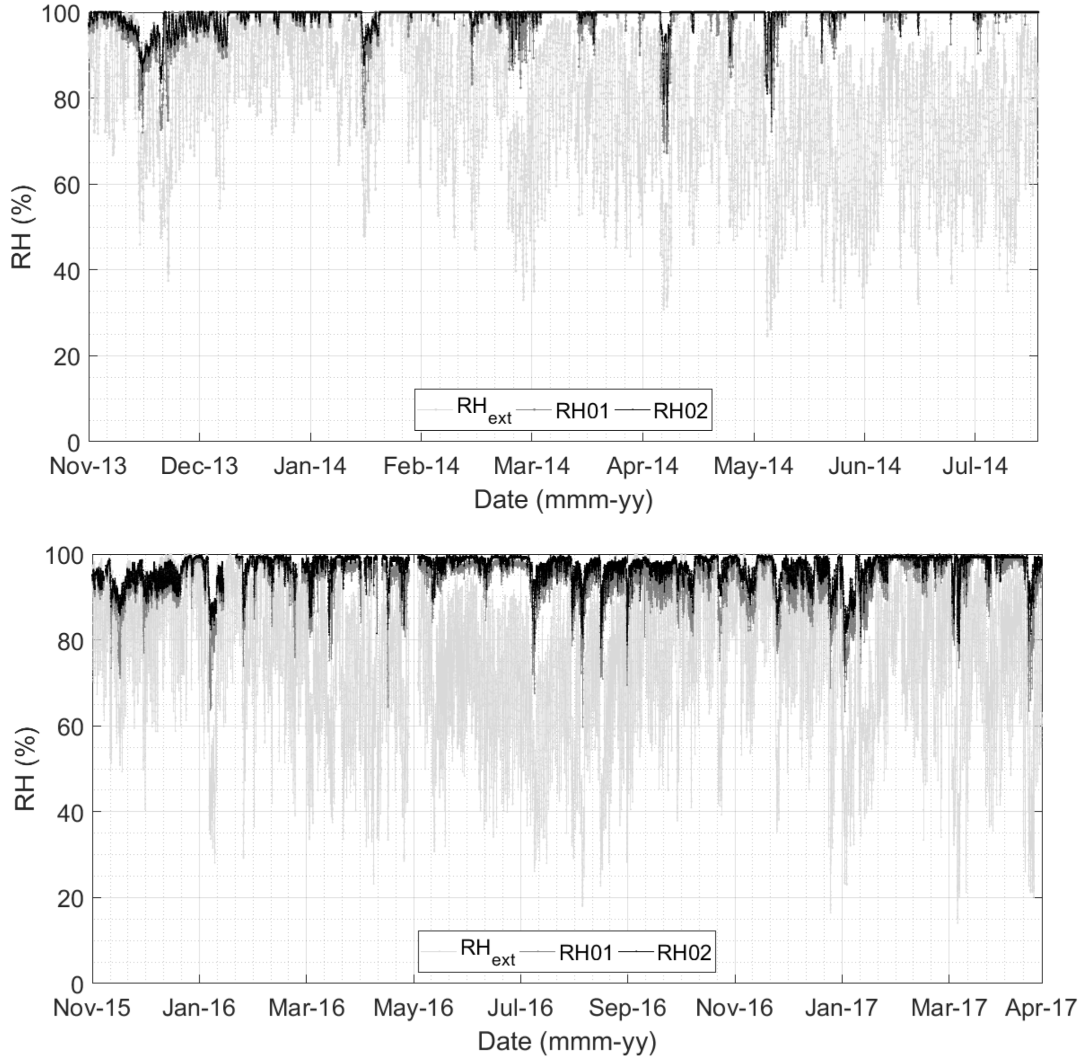

Figure 4. (a) Upper panel. Indoor and outdoor RH trends recorded inside the Mithraeum of the Caracalla Baths. Measurements were carried out with CCS. The RH was often over 90% and the minimum value reached was 67%. (b) Lower panel. Indoor and outdoor RH trends recorded inside the Mithraeum of the Caracalla Baths carried out with HCS. The RH is often over 80% and the minimum value is 31%.

To test whether there was a monotonic relationship between air flows (intensity and direction) and RH values (measured by both CCS and HCS), the Spearman's rank-order correlation [6] was used because any assumption on data frequency distribution is required.
A weak correlation was found with the air flow speed (Table 3), whereas a moderate correlation was found with the air flow direction. This may be attributed to the building structure which can influence the forces of the air flow directions, affecting RH fluctuations much more than the air flow intensity.

Table 3. Spearman's rank correlation coefficient values, between RH values and air speed, and direction values.

Spearman's rank correlation coefficient	CCS		HCS	
	Wd	Ws	Wd	Ws
RH01	0.37	-0.11	0.29	-0.19
RH02	0.37	-0.04	0.31	-0.15

4. Conclusions

This study has demonstrated that in the hypogeum environment, characterized by RH levels close to 100%, a thermo-hygrometric sensor with a heating cycle to prevent the saturation of the capacitive RH sensor, allows more accurate measurements. Differences in RH data collected by conventional RH capacitive sensors and heated capacitive sensors have been found in two different hypogea heritage sites, which suffer of degradation phenomena strictly related to high humidity.

In the Monkey Tomb, the RHs measured by the conventional capacitive sensor was always close to 100%, whereas those measured with the heated capacitive sensor show that RH can drop up to 94%. In the Mithraeum of the Caracalla Baths, the heated capacitive sensor measured decreases of RH up to 31%, while the conventional sensor measures a minimum value of 67%. Moreover, RH values seemed to be moderately affected by the air direction.

The heated capacitive sensor has resulted to be more effective in recording RH daily fluctuations. In fact, the heating cycle, allowing the desorption of water from the dielectric material, provides a RH measurement which is accurate and with a lower time response with respect to the capacitive sensor without heating cycle. This result should encourage the use of the heated capacitive sensor when indoor environmental conditions are characterized by such high RH values. A fast recording of RH drop is fundamental in hypogea environments, as it is able to detect short-term dry episodes which could affect their peculiar hygrometric conditions.

Acknowledgments

We are grateful to Dr. Giroldini of the SABAP-SI (Soprintendenza Archeologia, Belle Arti e Paesaggio per le province di Siena, Grosseto e Arezzo) for the access to microclimate data of the Monkey Tomb, and to Dr. Piranomonte of the Soprintendenza Speciale per i Beni Archeologici di Roma, for the access to microclimate data of the Mithraeum of the Caracalla Baths.

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