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Wireless Sensor System for Intelligent Facades

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ABSTRACT
The integration of a wireless-transponder system into building components ("intelligent building materials") with built-in relative humidity and temperature sensors (RH, T) allows for a cost-efficient and non-destructive measurement of data regarding the current hygro-thermal conditions of a building. Even during long-term use, quality assurance of the building system can be achieved by "looking into" the component. This supports the sustainability of the building from both a technical and an ecological point of view. In this paper, the development, the functionality and the exemplary application of Radio Frequency (RF), as well as an hygro-thermal analysis for solving the challenges of building-climatology planning is presented. Built on the measurement data of a real case study, the results of hygrothermal simulation tools are confirmed. Based on this, the use of thermal insulation in buildings for energy saving has been verified and the implementation into a hygrothermal simulation tool is shown. For the verification of results, a case study in Berlin was chosen, in which interior and exterior temperature and relative humidity values were recorded. Even with the peculiarity of irregular user behaviour of the building, good accordance between measured and calculated values could be achieved. Based on the analysis and evaluation of measurement data, as well as the implementation of hygrothermal simulations, the presented study provides a guideline for planning of ETICS with particular respect to extremely climate conditions.

KEYWORDS
hygrothermal, ETICS, intelligent façade, ultra-low power sensor system, wireless sensor node

INTRODUCTION
External thermal insulation composite systems (ETICS) on energy efficient façades are widely used under cold and hot climate conditions. However, the construction in both cases should be investigated in order to ensure avoidance of moisture damage. By an integration of wireless transponders into the installed insulation systems, it is possible to obtain information about the hygrothermal (temperature and relative humidity) condition of the system. In the case of critical measured values, concrete measures for the avoidance of damage (e.g. condensation within the construction, mold growth, algae) can be developed and implemented timely. In addition, the measured data can be compared with the results obtained from hygrothermal simulation tools that are used for verification and calibration of the data for further hygrothermal planning tasks. The wireless technology used here is a new transponder system with integrated humidity and temperature sensors. This system has been developed in order to check the material conditions in components such as exterior walls, ceilings or roofs, and to evaluate their structural-physical quality during the construction process. It allows for a non-destructive measurement data acquisition (cost effective, minimal effort) and an early detection of hygrothermally critical points within an insulated building structure, and thus contributes significantly to the prevention of structural damage. Traditional wired systems are cost intensive and always come with a high on-site installation effort (see figure 1). Moreover,

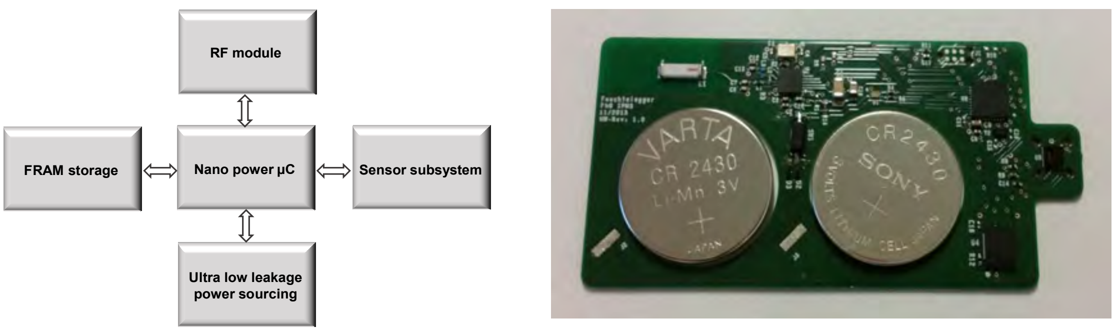
extra imperfections (thermal bridges) are introduced into the construction due to the wiring of the sensor and can bias the result. In addition, wired system could be installed only if power connection is available in situ. Wireless system can be installed also in inaccessible places.

a) b)

Figure 1 a) Traditional wired sensor system, b) Wireless sensor system in the adhesive layer

WIRELESS SENSOR SYSTEM

The main challenge for long-term monitoring systems is to provide energy for the operation for a long period of time. Traditionally, batteries are used to provide the energy for such a system. For the mentioned application of intelligent facades, size does matter: only small and low height electronic systems can be embedded into the facade in a simple way. This means that the energy supply cannot be enlarged indefinitely - only coin cell batteries can be used. This results in additional technical challenges, such as limited maximum discharge currents and self-discharges. These challenges have to be addressed when designing the wireless sensor system. The system is sourced from a pair of low leakage lithium manganese dioxide coin cells. Since it is difficult to change the batteries, the main focus of development of such a sensor system is the energy optimization of the whole system. This starts with the component selection, the hardware design, goes over to specific energy management and sleep strategies and optimized filter algorithms, and ends with an energy enhanced wireless protocol.



a) b)

Figure 2. a) Block diagram of the wireless sensor system, b) Wireless node of the system.

Figure 2 (a) shows the block diagram of the wireless sensor node hardware. To enable the intended operation duration of more than 3 years, the system uses two ferroelectric-random-access-memory blocks (FRAM). One of these blocks holds the program execution context for the microcontroller. This enables the implementation of a programming model, utilizing an ultra-deep sleep mode without active RAM retention while significantly reducing the system boot time and thus the energy consumption. The second memory block is for long-time storage of the recorded data, which is stored in a proprietary format. By choosing a FRAM technology, a non-volatile random access memory alternative to flash memory, the required energy for data storage is reduced by more than one order of magnitude, still guaranteeing the data retention for more than a decade and reducing the write/read times, which in turn reduces the energy consumption (Fujitsu, 2013). Figure 2(b) shows the final sensor node hardware before encapsulation. For wireless sensor systems, it is typical that the actual wireless transmission consumes the most energy in the system (Heinzelmann, 2000). Therefore, the design and optimization of the radio frequency sub-system is essential, and results in a large benefit for the operational time of the sensor system. For the described sensor system, a 2.4 GHz ultra-low power transceiver circuit has been selected. This circuit enables the design and implementation of custom wireless transmission protocols. The energy consumption of the transmitter circuit has been measured. Based on the measurements, an energetic model has been derived. Using this model, an energy optimized proprietary wireless communication protocol has been implemented. The protocol uses a net data rate of 2 Mbit/s with an automatic acknowledgement (ACK) packet generation and automatic retransmission of lost RF frames to ensure reliable wireless data transmission. The range has been limited to around 10 meters in indoor environments to reduce the energy consumption of the RF transmission. The sensor hardware uses an integrated humidity and temperature sensor circuit, which is connected to the microcontroller unit via the Inter Integrated Circuit (I^2C) bus (NXP, 2014), a standard bus to connect peripheral ICs to microcontrollers. The sensor itself is factory calibrated. The accuracy of the sensor system has been evaluated using several experiments in a climatic chamber and with long term measurements. At the time of writing, this evaluation test has run for 30 months, and will be continued until the battery stops supplying power. The measurement of the battery voltage does not show any sign of wear-out for the near future.

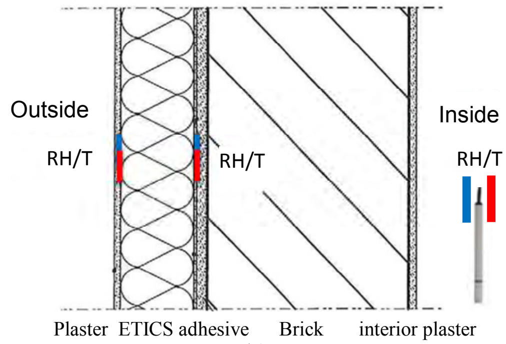
APPLICATIONS OF WIRELESS TECHNOLOGY IN BUILDING CONSTRUCTION

Digitization of building materials and components, by means of the above described innovative transponder system with integrated temperature and humidity sensors (e.g. insulation board, façade elements) is important to carry out non-destructive monitoring of components for further physical investigations of the buildings, and thus preventing structural damage. For this purpose, a digital temperature and relative humidity sensor, embedded in a wireless-transponder, is installed in a wall structure. SHT21 sensor was chosen for the case study described below. It provides calibrated, linearized sensor signals in digital format. It contains a capacitive type humidity sensor, a band gap temperature sensor and specialized analog and digital integrated circuits. This yields an unmatched sensor performance in terms of accuracy and stability as well as minimal power consumption. Every sensor is individually calibrated and tested. Also the resolution of SHT21 can be changed on command from 8/12bit (0,7/0,04%) up to 12/14bit (0,04/0,1°C) for RH/T. Accuracy tolerance are ±2%, ±0,03°C, hysteresis is ±1%, and operation range are 0% to 100%, -40°C to 125°C (Sensirion, 2014).

APPLICATION OF WIRELESS SENSOR SYSTEM IN A CASE STUDY IN BERLIN

With the goal of investigating the functionality of different ETICS by the use of a wireless measurement system and hygrothermal simulation tools, a case study in Berlin (Maerkische Scholle) was chosen. Five multi-story residential buildings are located in the same street, identical in terms of general dimensions, area, function, construction and direction. They were insulated with different insulation materials (EPS, hemp, wood fibre and mineral wool), and equipped with the newly developed measuring system as follows: Two measuring points were set up in each test house, points A and B (northeast façade, southwest facade). Each measuring point contains 3 sensors (RH, T), resulting in a total of 60 sensors. The reading out of the sensor systems takes place via a read-out station with a reading distance of 10 meter (see figure 3). The temperature and relative humidity are recorded within the construction, as well as inside and outside. This examines the moisture absorption of the plaster and the change of the insulating effect of the five ETICS under changing daily and seasonal conditions, with regard to their protective effect against summer heat, winter cold and rain.

a)



b)

Figure 3. a) The case study in Berlin, b) location of the RH/T Sensors in the building

MEASUREMENT RESULTS AND HYGROTHERMAL ASSESSMENT

In addition to the functionality of ETICS for reducing energy consumption, the hygrothermal situation and the indoor air quality should be examined for damage-free construction. For a hygrothermal performance assessment of the walls, the temperature and humidity measurements, recorded by above described innovative wireless sensors, were evaluated for buildings 1 to 5 at both sides of the insulation boards as well as indoors in each measurement section. The measurements of the test houses are shown in the sample below. Figure 4 (a) presents the measured temperature and relative humidity on hemp (measurements started October 17, 2016) under the plaster level as well as in the adhesive layer (between insulation and solid wall). At the beginning, the moisture in the adhesive layer is relatively high, which can be related to residual construction moisture, in addition to the fact that the apartment was not inhabited until mid-December. After that, the humidity drops significantly, remaining between 40 and 50% from December until the end of April, and raising to about 60% starting in May. The moisture under the plaster layer, in contrast to the moisture in the adhesive layer, rises significantly in winter and reaches the max. value of 100%, then beginning to decrease in March. The hemp moisture is also evaluated here according to the data-sheet of Scientific-Technical Association for Building Preservation (WTA). It defines a limit curve for the relation of temperature and relative humidity in the wood-pore to keep wood non-destructive (WTA 2002). For the evaluation the daily average values of temperature and humidity were used. Only in two days, at the beginning of the measurement, the hemp moisture slightly exceeded the limit; this is normal, because the flat was not heated and the building moisture had not dried out yet (see figure 4 (b)). Figure 5 shows the temperature profile on both sides of the hemp as well as of the mineral wool for comparison. We see that both systems keep the room-temperature relatively constant in summer as well as in winter. More precisely, the temperature on the inner side of the mineral wool is about 2 K higher than that on the inner side of hemp or wood fibre mainly in the summer. Hemp reacts slowly to the outside temperature, compared to mineral wool. It has a temperature time shift of about 4-6 hours. This is due to the high heat storage capacity of hemp and wood fibre, and provides also a positive feature for the summer heat protection. The temperature time-shift between that of hemp und that of mineral wool can be seen clearly in figure 5 (b), which presents the temperature curves on both sides of insulation board during a 3- days period in a bigger scale.

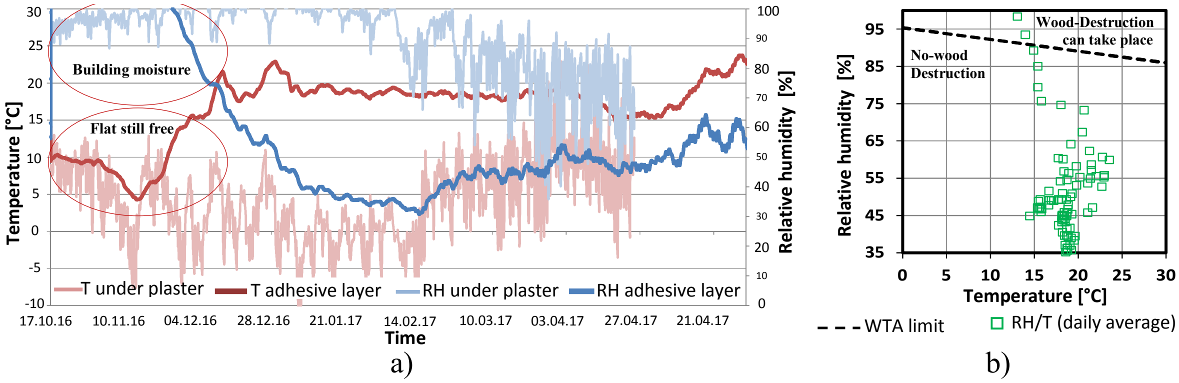


Figure 4. a) Measured RH/T on both sides of hemp, b) Evaluation of hemp RH/T by WTA

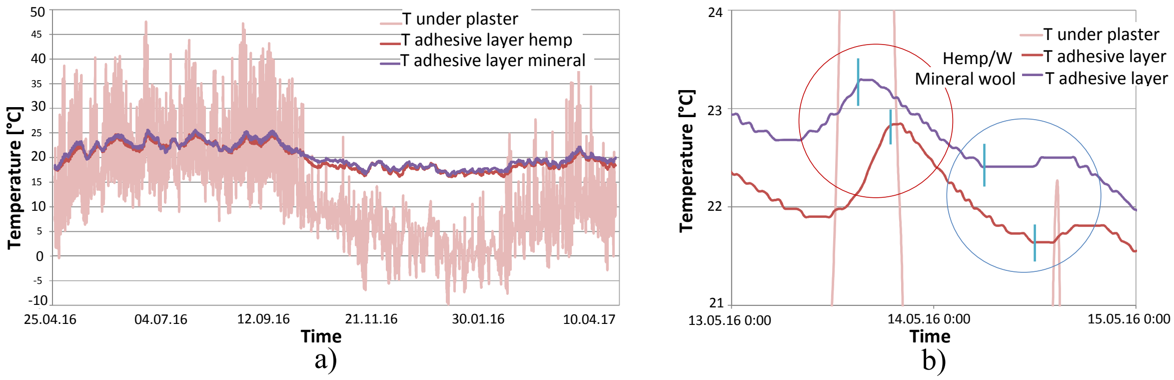


Figure 5. a) Measured temperature on both sides of the wood fibre, hemp and mineral wool, b) The same measurements in bigger scale during a period of three days

The conditions for mold growth on the inner wall surface depending on the indoor climate are also evaluated according to ISO 15026/13788 in all five buildings with four different ETICS. Here the daily average of absolute indoor humidity is assessed (calculated as a function of measured indoor relative humidity and temperature). Figure 6 shows the evaluations of buildings insulated with hemp (a) and with mineral wool (b) in comparison. All values of the building insulated with hemp are below the limit for normal occupancy (conditions for mold growth not given). For the building insulted with mineral wool few values exceed the limit for normal occupancy, and in about 7- days the values exceed even the limit for high occupancy.

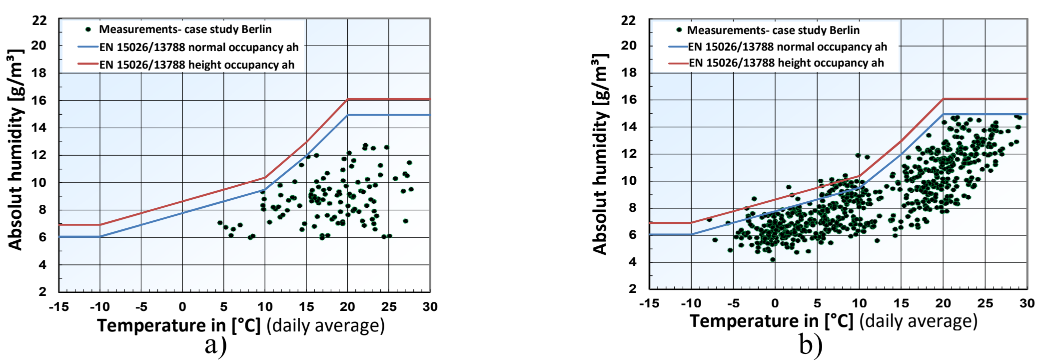
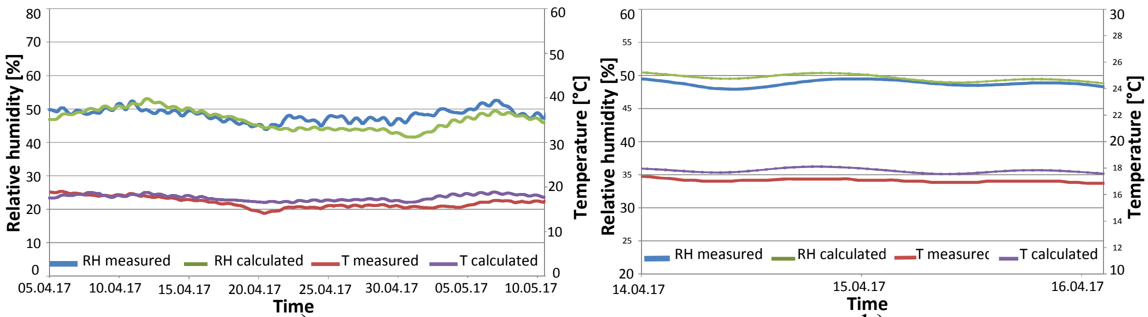


Figure 6. a) Relationship between outdoor air temperature and indoor absolute humidity for the building insulated with hemp, b) the same for the building insulated with mineral wool

COMPARISON OF THE MEASUREMENT AND SIMULATION RESULTS

For the comparison of the measurement and simulation results the hygrothermal model WUFI® is used (WUFI-Manual, 2015). For the calculation, the real outdoor climate conditions of Berlin and a constant indoor climate (20°C, 50%) according to ASHRAE 160 as well as the all hygrothermal material parameters, determined in laboratory (thermal conductivity, vapour division resistance, water absorption coefficient, thermal capacity, porosity) are considered. Figure 7 shows an exemplary comparison of measured and simulated relative humidity and temperature between hemp and massive wall. The results of calculated and measured RH/T are in good agreement. Little deviation is seen on occasion, which can be attributed to user behaviour (inconstant indoor climate). However, both results indicate moderate moisture values between hemp and massive wall. Since the calculation results using WUFI® are in good agreement with the measured one, the simulation model could be used for hygrothermal calculations, which could be needed for further analysis considering real climatic conditions.



a) b)

Figure 7. a) Measured and calculated (RH, T) between wall and hemp, b) The same in 4 days

CONCLUSIONS

On the basis of wireless technology an innovative sensor system for the humidity and temperature measurements (RH, T) has been developed. For ensuring a long-lasting, energy-efficient and performing measuring system an energy model has been derived from lab measurements and thus an optimized wireless protocol was implemented. Using this developed wireless technology, non-destructive effective measurement and diagnosis about the current state of building component were recorded and evaluated. Additionally to the fact that insulation does have a big effect of significantly reducing the heat flow through the wall, the results of the wireless system show that measuring after two years, no damage and no rain penetration were found in all variants. The moisture content of hemp/wood fibre ranged between 8 - 12M%. Hemp and wood fibre have a positive effect on summer heat protection. The indoor climate in both buildings, insulated with hemp and wood fibre, is comparable to other systems. So the conditions for mold growth on the inner wall surface are not given. This study proves that, an intelligent façade with integrated wireless- sensors (RH/T) guarantees a long-term, damage-free construction, during building use, by “looking into” the construction.

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