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"Gheorghe Asachi" Technical University of Iasi, Romania

COST-EFFECTIVE TECHNOLOGIES TO CONTROL INDOOR AIR QUALITY AND COMFORT IN ENERGY EFFICIENT BUILDING RETROFITTING

Gian Marco Revel[1], Marco Arnesano[1*], Filippo Pietroni[1], Jürgen Frick[2], Manuela Reichert[2], Katrin Schmitt[3], Jochen Huber[3], Martin Ebermann[4], Umberto Battista[5], Franck Alessi[6]

[1]*Università Politecnica delle Marche, Department of Industrial Engineering and Mathematical Science, Ancona, Italy*
[2]*University of Stuttgart, Materials Testing Institute Stuttgart, Germany*
[3]*Fraunhofer Institute for Physical Measurement Techniques, Freiburg, Germany*
[4]*InfraTec GmbH, Germany*
[5]*Stam srl, Italy*
[6]*Laboratoire d'Energétique du Bâtiment – CEA, INES, le Bourget du Lac, France*

Abstract

This paper presents a toolset for the efficient control of the indoor air quality and thermal comfort in retrofitted buildings. The refurbishment of existing buildings, compliant to actual regulations, often leads to airtightness and the consequent poor conditions for the occupants that could cause low productivity and even sickness. For this reason, the CETIEB (Cost Effective Tools for Better Indoor Environment in Retrofitted Energy Efficient Buildings) project developed innovative low-cost solutions to monitor and control the indoor air quality and thermal comfort. Among the technologies developed, this paper presents ad-hoc sensors for the monitoring of Total Volatile Organic Components (TVOC), CO_2 and thermal comfort together with a control logic that, using measured data, provides the optimal rules to actuate the control devices (ventilation, heating/cooling, windows opening, shutters operation and so on). The application and validation of the integrated solution, monitoring plus control logic, was performed in a laboratory building to compare the performance of the proposed solution with the traditional system employed in buildings. The results turned out to show sensors performances comparable with commercial solutions but with a significant reduction of costs. Moreover, the application of the integrated solution showed an improvement of the indoor air quality and comfort with a 15% of energy saving, compared to the traditional thermostatic control.

Key words: energy efficiency, gas sensor, HVAC control, indoor air quality, thermal comfort

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1. Introduction

The built environment is the place where people spend 60-90% of their life (European Commission, 2011) and where about the 40% of the European energy is consumed (European Commission, 2009), also to maintain and guarantee the required living quality. It is estimated that HVAC (Heating, Ventilation and Air Conditioning) energy consumption accounts for 10 ÷ 20% of total energy consumption in developed countries (Pérez-Lombard et al., 2008). The problem of achieving healthy and comfortable buildings is well recognized by scientific community (Ioan and Ursu, 2012) and, for example, Mendell (2007) demonstrated that improving the indoor air quality could bring to increased productivity, reduced sick leave and medical costs and prevention of potential liabilities. Thus, buildings

* Author to whom all correspondence should be addressed: e-mail: m.arnesano@univpm.it; Phone: +39 0712204508; Fax: +39 0712204801

have to provide the best indoor living conditions but with the minimum energy use (Kalmár and Zöld, 2011). It is clear how the two objectives could easily go in opposite directions. In fact, the reduction of the energy consumption requires a high level of air tightness to ensure low outward leakage and this could lead to health problems as described in (Sharpe et al., 2015). Given this background, one of the main possibilities to face the issue of maintaining indoor air quality in compliance with the energy regulations is the inclusion of advanced monitoring and control methodologies to be entailed in the traditional HVAC systems together with the adoption of ad-hoc materials, e.g. exterior walls (Giuşcă et al., 2009), as replacement of the traditional ones. To this aim some studies investigate procedures for the indoor building assessment, as the one presented by (Capolongo et al., 2013) or developed monitoring methodologies and tools to improve the efficiency of HVAC management (Revel and Arnesano, 2014a, 2014b) and the overall building management (Grindvoll et al., 2012). However, even if procedures and methodologies are well-known, actual commercial solutions for the real-time monitoring and control of the indoor air quality are not able to take into account the full spectrum of parameters required to assess the air quality or, if able, they are too expensive especially in the case of building retrofitting.

The FP7 European project CETIEB (Cost Effective Tools for Better Indoor Environment in Retrofitted Energy Efficient Buildings) replied to this requirement with the development of a toolset specific for the improvement of the Indoor Air Quality (IAQ) in energy efficient refurbishment projects. The toolset includes ad-hoc sensor networks, innovative sensors and active/passive control systems. Each component was developed with the aim of overcoming limits of the actual solutions or to provide improved functionalities with a cost reduction. The resulting toolset entails sensors for the continuous monitoring of VOCs (Volatile Organic Compound), CO_2, light and thermal comfort sensors, HVAC control systems and biofilters for the active air cleaning, new materials for the passive control of the environment, such as photo-catalytic plasters and light materials with low thermal conductivity.

The overall approach of the technologies developed in the CETIEB project was presented in a previous paper (Revel et al., 2013). This paper presents the results achieved with the monitoring tools and active HVAC control. A test building was used to compare the cost-effective environmental control developed with respect to the traditional systems.

The paper illustrates the comparison of the indoor air quality and energy consumption of two identical rooms, the reference one equipped with traditional thermostat and ventilation control, the test one equipped with the monitoring and control tools developed in the project. The aim of this paper is to demonstrate how the environment can be better controlled to achieve the required indoor air quality with the lower energy consumption.

2. Materials and methods

In the following sections, the innovative sensors (VOC, CO_2 and thermal comfort) and the environmental control logic developed within CETIEB are presented, together with information about their performances, obtained with ad-hoc laboratory tests conducted.

2.1. Detection of VOC

Within CETIEB, innovative sensor technologies have been developed to monitor indoor air quality. In particular, the focus has been on volatile organic compounds as indicator for health status of the subject in a room. The objectives of the VOCs sensors development have been their qualitative and quantitative assessment, while providing affordable and small-sized systems for integration in smart sensor networks. According to the state of the art for VOC monitoring, mainly metal-oxide gas sensors are used. They offer low-cost, small-sized solutions and are able to detect VOC levels with enough accuracy. However, the referred output of such sensors is the total volatile organic compound level, as they cannot distinguish different VOCs (e.g. alcohols, ketones, aldehydes). The detection of such single compounds can be performed through optical sensors, by performing analysis in the infrared wavelength range. For these devices, the resolution is generally low, because of the not sufficient optical power. In fact, the infrared light sources power decreases with wavelength and is generally not adequate in the range 8÷12μm, where there is the maximum absorption of most of the VOCs. For this reason, two low-cost solutions have been developed for the monitoring of VOCs: a gas sensor array consisting of four metal-oxide (MOX) sensors and a spectroscopy-based VOC sensor to monitor selectively the typical indoor contaminants absorbing in the mid-IR range. The MOX sensors (Fig. 1a) are commercially available low-cost products (< 100 €), which are combined to a sensor node: the combination of the measured gas signal can be used to gain additional benefit by pattern recognition. The other device (as shown in Fig. 1b) is a miniaturized and compact spectrometer for the IR-range. Compared to huge and cost-intensive laboratory IR spectrometers, this sensor delivers an absorption spectrum of the target gas in a reduced IR-range, but is much more effective concerning size and costs. Broadband emitter, pyroelectric detector, tunable filter and long path cell are components which can reach prices in the range of several tens of Euros in higher quantities, while a single sensor is estimated to be near the thousands Euros.

Methane and acetaldehyde have been used as test gases for indoor air quality assessment with the spectroscopic system.

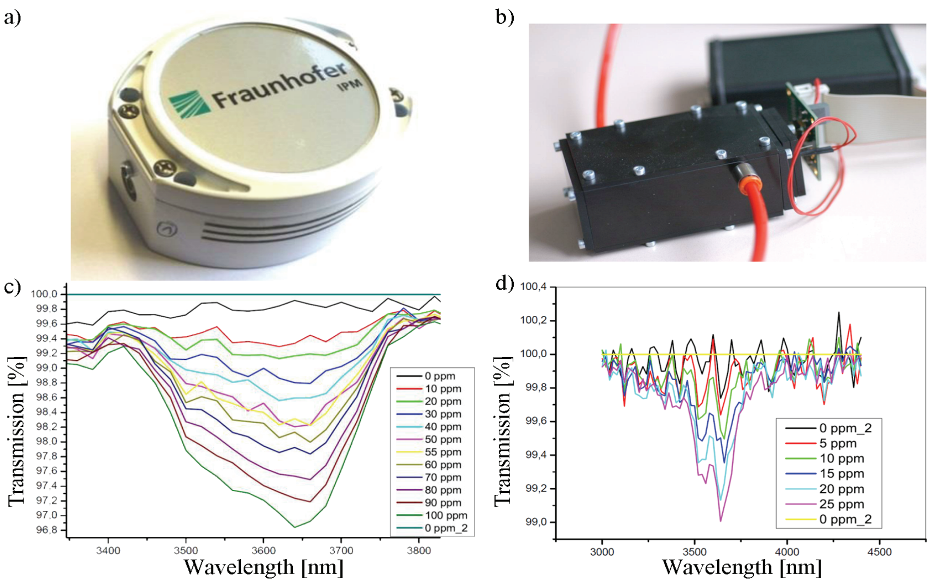

Fig. 1. (a) Gas array sensor; (b) spectroscopic sensor; (c) Measurement of acetaldehyde in N_2 from 0÷100 ppm in 10 ppm steps; (d) Measurement of acetaldehyde in N_2 from 0÷25 ppm in 5 ppm steps

Acetaldehyde (peak absorption at 3.65 µm) was measured from 0-100 ppm in N_2 in 10 ppm steps. The Maximum Allowable Concentration (MAC) for acetaldehyde is 50 ppm, so that this concentration needs to be reliably detected (Figs. 1c and 1d). The Limit of Detection (LOD) for acetaldehyde has been determined to be lower than 10 ppm.

2.2. CO_2 measurement

The CO_2 is one of the crucial parameters to assess the indoor air quality and it is directly linked with the occupancy. For indoor environments, concentrations above 1000 ppm are known to cause fatigue, headache and dizziness in people, while from 1500 ppm, usually, people begin to feel sick (Myhrvold et al., 1996). To maintain the well-being of occupants, the CO_2 level should be monitored constantly (with enough accuracy) and maintained at a level close to the atmosphere (around 390 ppm). The solution developed within CETIEB is based on the working principle of filterphotometry that makes use of the specific absorption of infrared (IR) radiation of molecules. A basic filterphotometer comprises an emitter and a detector with IR-filters. The absorption path between these two optical elements defines the measurement range. A longer path enhances the statistical possibility of a molecule to absorb a photon and results in a higher accuracy. A 2-channel filter photometer based on two commercial detectors and two different filters has been adopted. The first filter has a high transmission at 3.95 µm and serves as reference. In fact, no specific molecule absorbs in this band. With this filter, signal drifts of the optical components can be detected and compensated. The transmission peak for the second filter is at 4.25 µm, where CO_2 has its main absorption band. The absorption path has been chosen equal to 3 cm, in order to cover the relevant concentration range for indoor air quality measurements. The IR filters have been placed in front of the detector to define the molecule-specific wavelength bands of interest. Both the thermal emitter and detector have been placed within an aluminum tube-shaped housing that defines the absorption path and at the same time serves as mechanical protection for the sensor element. An electronic control unit (Fig. 2a) has been developed to control all the optical components and to process the detector signals. The combination of both filters and absorption path, as described previously, allows a measurement range from 0÷20.000 ppm.

The sensor performance was assessed with a dedicated calibration conducted in laboratory, using different CO_2 concentrations in a standard gas (N_2). Figs. 2c and 2d show an example of the sensor response (0÷20000 ppm) during a test conducted in laboratory. The system was placed into a large chamber of about 1 dm^3 volume to simulate a real situation as in indoor environments. The CO_2 concentration was varied at fixed time intervals, covering a range from 0÷20000 ppm. The test showed a limit of detection of 20ppm with an accuracy of about ±50ppm.

2.3. Continuous thermal comfort monitoring

A low-cost infrared-based system for the real-time monitoring of human thermal comfort has been developed to provide the same information of traditional microclimate stations (assumed as the gold standard for short-term monitoring), but with a decrease of costs in the order of 1/10 of the station and with potentials for real-time and spatial measurements. The system (prototype version in the range of 200 ÷ 240 €) is based on a microcontroller, sensors and embedded algorithms to derive the thermal comfort index PMV (Predictive Mean Vote) for multiple positions in the room. PMV is a standard index (according to ISO 7730), which predicts the mean votes of a large group of people on a seven-point thermal sensation scale, from -3.0 ("Cold") to +3.0 ("Hot").

Four environmental parameters (air temperature, relative humidity, air velocity and mean radiant temperature) and two personal parameters (metabolic activity and clothing level of the subject) need to be measured or provided in order to apply the methodology and calculate accurately the PMV value.

The working principle and measuring performances have been described in (Revel et al., 2012, 2014a). The solution consists of three main parts (as shown in Fig. 3):

- The IR scanning system, fixed on the ceiling of the room so to allow the continuous measurement of surfaces temperature and calculation of mean radiant temperature maps (in agreement with the methodology proposed in the ISO 7726 standard);
- The control unit, managing the data flow between integrated sensors (indoor temperature, relative humidity and air velocity) and from/to the user interface where the thermal comfort for multiple positions is calculated;
- A dedicated user interface (e.g. for Android devices), for setting data input and data storage for further analysis.

Each sensor is able to provide accurate measurement of indoor thermal comfort in medium spaces (< 100 m^2, maximum distance of about 5 m from the surface to monitor). More than one sensor should be installed in the case of larger environments (i.e. open spaces), eventually with optimized positioning so to reduce the sensors number.

Several tests were conducted to provide the metrological characterization of the system developed (e.g. tests in controlled environments as in Revel et al., 2014b). The final performances of the system are summarized in Table 1.

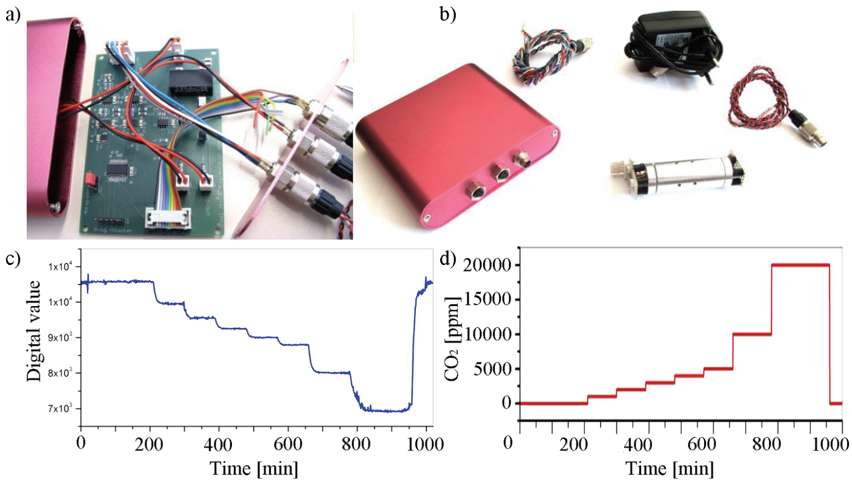

Fig. 2. (a) Assembled circuit board of CO_2 sensor; b) The final prototype developed; (c) sensor raw reading during the laboratory test; (d) resulting CO_2 concentration during the laboratory test

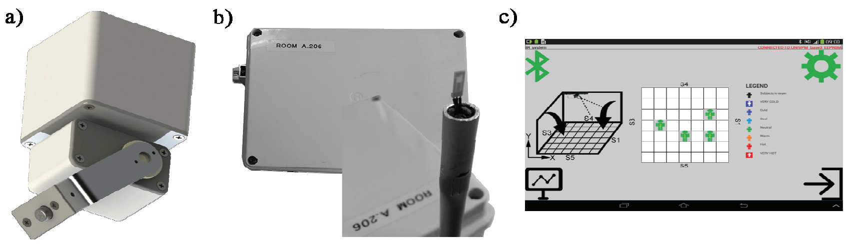

Fig. 3. Thermal comfort measuring tool. (a) IR scanning system; (b) Control unit and integrated sensors; (c) User interface for smart devices

Table 1. Performances of the system developed for the environmental parameters measurements

Parameter	*Methodology*	*Accuracy*
Air temperature	Direct measurement	±0.3°C
Relative humidity	Direct measurement	±2%
Air velocity	Direct measurement	±0.1m/s
Surface temperatures	Direct measurement	±0.9°C
Mean radiant temperature	ISO 7726 methodology from surface temperatures measurement	±0.5°C
Predicted Mean Vote	ISO 7730 methodology	±0.2

The system is able to provide the continuous measurement of PMV index with an accuracy of ±0.2 units. Several tests conducted in real spaces (offices, classrooms) demonstrated the potentials of using the thermal comfort system to provide continuous information about the real thermal perception of the users. For example, Fig. 4 shows results from two measurement campaigns (summer season in a) and winter season in b)) conducted in an office room. The PMV profile measured by the system presents little deviations (0.1±0.1 and 0±0.2 respectively) with respect to the traditional microclimate station (HD32.1 from DeltaOhm).

These results confirm the performance of the device for the continuous measurement of thermal comfort and the potentials of using such measurement to apply an optimized HVAC control by means of this index.

2.4. Development of optimized IAQ and PMV-based control algorithms

The HVAC systems are designed to maintain good indoor air quality through adequate ventilation and provide thermal comfort. HVAC systems are among the largest energy consumers in buildings (i.e. they account for 39% of the energy used in commercial buildings). Consequently, almost any business or government agency has the potential to realize significant savings by improving its control of HVAC operations and improving the efficiency of the system it uses. Moreover, a correct indoor ventilation is necessary to allow carbon dioxide to go out and oxygen to get in, making sure that people are inhaling fresh air. Indoor air quality is a major challenge in energy efficiency as enhanced air tightness improves the comfort with direct impact on medical costs, as well as improvement in both people's productivity and concentration level. Control strategies and algorithms have been developed within the project to control both IAQ and thermal comfort. The main scope is to ensure IAQ staying within acceptable limits, improving the global comfort of the room and energy efficiency.

The control system developed is rule-based and is composed of two main modules: the first one focused on IAQ, the second one on thermal comfort, making use of the PMV index.

IAQ is satisfied when the concentration of the pollutant considered (CO_2, TVOC) is under the acceptable limits, while thermal comfort is satisfied when the PMV is between ±0.5. The priority has been given to IAQ, meaning that the thermal comfort would be ensured only once the pollutants concentration is under the limits. The control structure developed is potentially applicable to any kind of indoor environment and monitoring system, e.g. taking advantage of the IR-based thermal comfort system developed within CETIEB (an example of the routine implemented is shown in Fig. 5).

2.5. Experimental

An experimental test was performed in a real building (Fig. 6.) of the INES (*Institut National de l'Energie Solaire*, France) platform in order to test the potential of using the thermal comfort system (in combination with a dedicated PMV-based HVAC control algorithm) to improve the indoor comfort. The demo site was modified in order to provide two identical rooms (geometry, orientation, HVAC system and monitoring devices) and to monitor continuously their behavior with and without the control algorithms. In particular, a test similar to the one described in (Yang et al., 1997) was conducted. In the first room (referred as Test Room) the microclimate was controlled with the PMV-based approach, i.e. the continuous measurement provided by the thermal comfort system and the rule-based architecture developed in the project. In the other room (referred as Reference Room) a constant temperature set point of 24°C was maintained so to replicate the traditional thermostatic control.

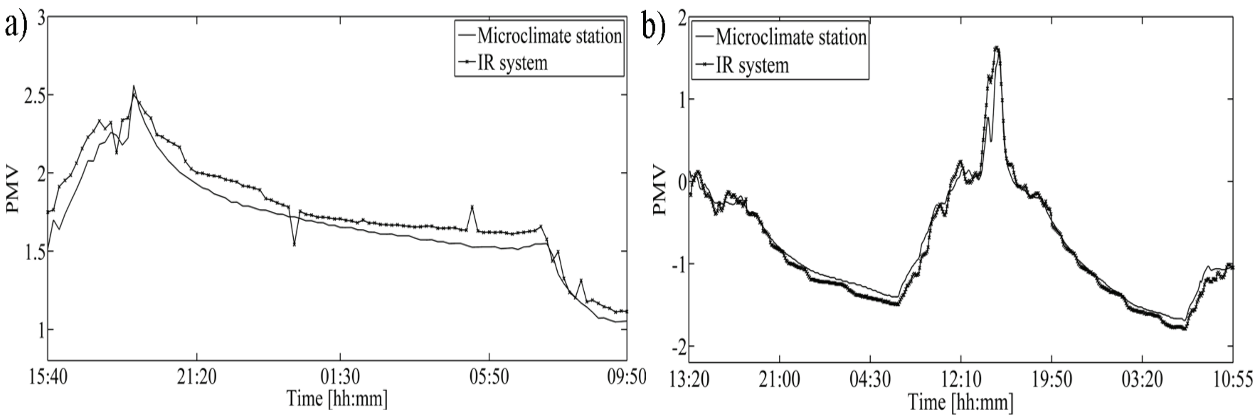

Fig. 4. Comparison of the thermal comfort measurement performed by the system developed with respect to the microclimate station

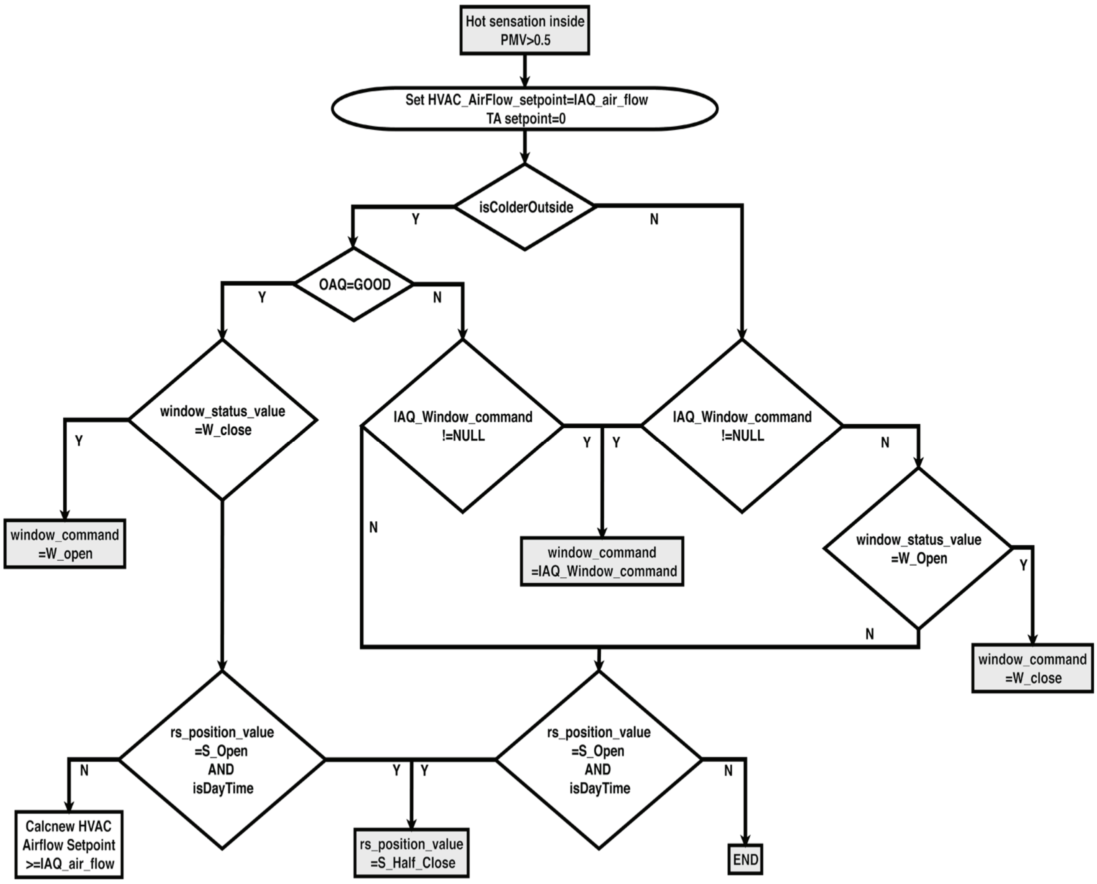

Fig. 5. Rules architecture to control IAQ and thermal comfort

(a) (b)

Fig. 6. (a) Building in the INES platform for the test conducted; (b) Thermal comfort system placed on the ceiling of Test Room for the test

According to the sensors and actuators available in the rooms, the control algorithm was able to regulate the room ventilation, air temperature and incoming solar radiation (window opening, rolling shutter, inlet/outlet fans, electrical heating system). A LabView software was implemented to manage the devices used to control the systems and to monitor the environmental parameters. Therefore, IAQ (CO_2 and TVOC) was also monitored in this test through commercial sensors. A standard TCP/IP communication protocol was implemented for the thermal comfort system in order to provide the continuous measurement (environmental parameters and PMV) to the HVAC control algorithms, with a sampling frequency of one measurement each 5 minutes. Then, the control algorithm made use of those data to identify the best actions to perform and sent them as input to LabView platform through a web-service. Both rooms were also equipped with energy meters to measure the electrical consumption and compare the results after the application of the proposed approach.

3. Results and discussion

The test lasted one week, during which the Reference and Test rooms ran with the traditional and innovative control system respectively. The

PMV computed in the rooms by the thermal comfort systems was compared to the one calculated from the environmental sensors installed and the results are shown in Figs. 7 a) and 7 b). Both the systems measured similar profiles (deviations of -0.1±0.1 and -0.1±0.2 in test room and reference room respectively), validating the performance of the low-cost solution developed. It can be noticed that an improvement of the thermal comfort (around one unit during the hot hours and mitigated variations) was achieved in the Test Room after the application of the PMV-based algorithm. Again, similar improvements can be observed for the indoor CO_2 concentration (Fig. 7c), where an average reduction of around 100 ppm was obtained in the Test Room.

The control system was able to actuate the window shutter and the inlet/outlet airflow (no heating or cooling, only mechanical ventilation). The strongest improvement in the thermal comfort was obtained by the control of the shutter. In fact, the indoor total solar radiation measured in the test room was strongly reduced (Fig. 8a) and this turned out to provide an improvement in the comfort conditions (a deviation with respect to the reference room from 0.5 up to 1.0 unit when the solar radiation contribution is maximum). The highest improvement in the thermal comfort was reached when the solar contribution was maximum, central zone of maps reported in Figs. 8 a) and b).

In fact, the strong contribution to the mean radiant temperature due to direct and diffuse solar radiation was reduced in the test room with an adequate control of the shutter. Because of this, a significant improvement in the thermal comfort (denoted by a higher deviation with respect to the reference room) was obtained as shown in Fig. 8b) where the central zone becomes colder from the 04/13/2014 when the optimal control is actuated.

The test conducted highlighted the efficiency of the system in improving both the IAQ and the thermal comfort with an energy saving. In fact, the proposed control system allowed an energy saving of the 15% (2804 Wh in the test room, 3293 Wh in the reference room) during the week of testing.

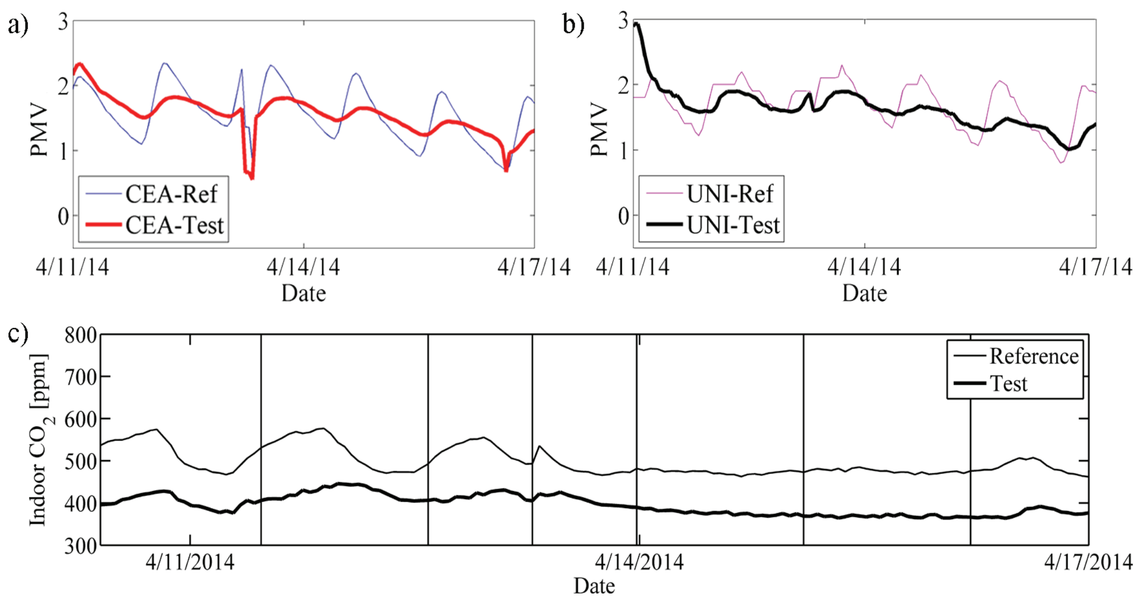

Fig. 7. (a) PMV calculated in post processing from the environmental sensors installed; (b) Continuous measurement provided by the thermal comfort systems developed; (c) Improvement in the indoor CO_2 concentration in Test Room after the application of the PMV-based approach

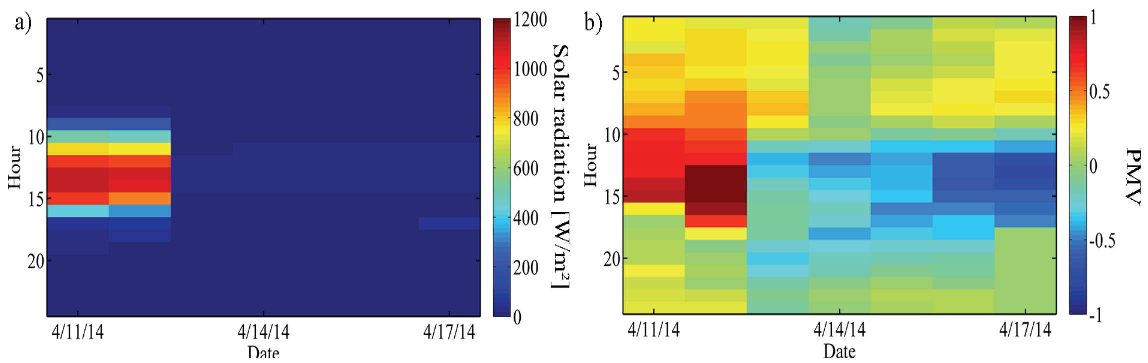

Fig. 8. (a) Indoor total solar radiation measured in test room during the measurement campaign; (b) PMV deviation between Test Room and Reference Room

4. Conclusions

The innovative solutions developed within the CETIEB project and discussed in the paper allow the cost-effective monitoring and control of the indoor environment for optimal living conditions with the lower energy consumption. The results obtained from the laboratory testing of the sensing devices presented are comparable: in fact, they are all able to reproduce the performance of typical solutions currently used, but with reduced cost and high integration capability, overcoming the limits in the market. For example, the solution developed for the thermal comfort allows measurements of the PMV for all the occupants in the operational phase with IR-based sensor, which is not feasible up to now with the commercial instrumentation available.

The potential of integrating the information provided by these sensors in an optimized HVAC control algorithm leads to an improvement of the perceived thermal comfort and energy efficiency. This has been initially demonstrated with the test conducted in the test building, as reported in the paper, where an improvement of the IAQ and thermal comfort was obtained with the reduction of about the 15% of energy consumption. Thus, the complete solution developed in CETIEB is able to improve significantly the indoor air and environmental quality by means of a cost-effective monitoring, with cheap tools embedded in a modular sensor network and optimized control actions.

Further tests could be useful to demonstrate the potential of such technologies in the improvement of the indoor air quality.

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