Development of a low-cost temperature data monitoring.
An upgrade for hot box apparatus

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Abstract. The monitoring phase has gained a fundamental role in the energy efficiency evaluation of a system. Number and typology of the probes depend on the physical quantity to be monitored, and on the size and complexity of the system. Moreover, a measurement equipment should be designed to allow the employment of probes different for number and measured physical quantities. For this reason, a scalable equipment represents a good way for easily carrying out a system monitoring. Proprietary software and high costs characterize instruments of current use, thus limiting the possibilities to realize customized monitoring. In this paper, a temperature measuring instrument, conceived, designed, and realized for real time applications, is presented. The proposed system is based on digital thermometers and on open-source code. A remarkable feature of the instrument is the possibility of acquiring data from a high and variable number of probes (order of hundred), assuring flexibility of the software, since it can be programmed, and low-cost of the hardware components. The contemporary use of multiple temperature probes suggested to apply this instrument for a hot box apparatus, although the software can be set for recording different physical quantities. A hot box compliant with standard EN ISO 8990 should be equipped with several temperature probes to investigate heat exchanges of a specimen wall and thermal field of the chambers. In this work, preliminary tests have been carried out focusing only on the evaluation of the prototypal system’s performance. The tests were realized by comparing different sensors, such as thermocouples and resistance thermometers, traditionally employed in hot box experiments. A preliminary test was realized imposing a dynamic condition with a thermoelectric Peltier cell. Data obtained by digital thermometers DS18B20, compared with the ones of Pt100 probes, show a good correlation. Based on these encouraging results, a further test was carried out in hot box, comparing the data measured by digital thermometers, Pt100 and T-type thermocouples. In this case also, the analyses show a good correlation between either digital thermometers and analog sensors. From these results, it is reasonable to foresee that this measuring instrument could help those willing to realize or refurbish a hot box apparatus, and those who want to undertake temperature monitoring.

Keywords: temperature measuring instrument; hot box apparatus; flexible and low-cost instrument.
1. Introduction

The monitoring phases of energy systems allow to assess their real behavior, highlighting possible challenges. Frequently, proprietary software and high costs characterize instruments of current use, thus limiting the possibilities to realize customized monitoring and adversely affecting costs, flexibility, and data integration. For these reasons, customized measurement equipments are rapidly increasing and find application in many fields. Arnold et al. [1] presented an apparatus that allows to monitor and record high-temperature thermocouple measurements of dynamic systems in real time, with wireless network technology, to bridge the gap between a dynamic (moving) sample frame and the static laboratory frame. Gad and Gad [2] discussed a new sensor-based temperature data acquisition system for solar energy applications that allows flexibility and ease of changing the type of sensors and way of recording data. This system is especially suitable for large and remote installations where cost is a key factor in the choice of the measuring system. In the work of Ali et al. [3] the Open Source Building Science Sensors (OSBSS) project, created to design and develop a suite of inexpensive, open source devices based on the Arduino platform for measuring and recording long-term indoor environmental and building operational data, is presented. Revel et al. [4] disclosed a low-cost infrared measurement system, developed to monitor in real time thermal comfort conditions in indoor environments.

For the building sector, which is responsible for more than one third of the total energy use and associated greenhouse gas emissions, both in developed and developing countries [5], temperature monitoring phases represent a fundamental aspect, in order to evaluate energy performance and possible energy efficiency interventions. Indeed, the knowledge of the thermal behavior of buildings is an essential component of the strategies of the policy makers and energy efficiency is a key issue for the energy policies of the most industrialized countries [6].

In this paper, a flexible, low-cost and multi-probe measuring instrument is presented. The system is based on a microcontroller board ATmega2560 [7], that allows to measure and record simultaneously a large number of digital temperature probes, type DS18B20 [8]. The flexible management of the employable sensors is allowed through an optimized algorithm, that manages the microcontroller and automatically recognizes the number of probes really used.

Based on high flexibility and high number of temperature probes, the proposed measuring instrument fits well for laboratory tests in hot box apparatus. Since a hot box allows to assess energy performance of structural members with real dimensions, a large number of temperature probes is needed, in order to evaluate all the heat exchanges. Usually, to simplify the management of these temperature probes, commercial measuring instruments are used, but with high costs and poor flexibility. Martin et al. [9] evaluated the thermal response of thermal bridges through the guarded hot box of the LCCE (Construction Quality Control Laboratory) of the Basque Government in Vitoria-Gasteiz, equipped with a group of 86 T-type thermocouples inside each of the chambers (hot and cold), which measure the temperature of the air and the sample surface. Asdrubali and Baldinelli [10] discussed calibration and experimental procedures of the calibrated hot box of the Department of Industrial Engineering of the University of Perugia, taking into account three standards for calibrating hot boxes: the European EN ISO 8990 [11], the American ASTM C1363-05 [12], and the Russian GOST 26602.1-99 [13]. This calibrated hot box is equipped with 142 T-type thermocouples inside the hot and cold chambers, and 69 differential thermocouples to assess the temperature differences between the metering chamber and the external ambient. Chen and Wittkopf [14] used a calorimetric hot box to measure thermal transmittance of fenestration systems in summer condition. Integrated in the walls are sensors to monitor the heat loss through the walls using a 112- junction thermopile system, made of T-type copper-constantan thermocouple wire. Kus et al. [15] conducted a study to evaluate hygrothermal performance of pumice aggregate concrete (PAC) block walls using a calibrated hot box method, equipped with 52 NiCr–Ni (K) type thermocouples for measuring indoor and outdoor temperatures, surface temperatures of wall blocks, and the hollow walls inside the blocks.
The proposed system has been tested in the guarded hot box of the G. Parolini Lab. of University of L’Aquila, described and employed in previous works [16, 17]; the results obtained have shown good response of the system and good correlation between digital thermometers DS18B20 and analog probes (Pt100 and T-type thermocouple).

2. Methodology

The methodology applied for this work is synthetically shown in figure 1. The first step was to define the concept and all the properties required for the temperature measuring instrument. The following phases focused on the software and hardware design, which allowed the realization of the prototype and its laboratory tests. Finally, experimental analyses have been performed, in order to verify the actual performance of the measuring instrument.

![Figure 1. Methodology flow-chart.](image)

2.1 System description

The systems that need many analog temperature probes, such as an hot box apparatus, are usually based on data loggers with a limited number of input temperature probes. For this reason, the total cost of the measuring instruments has high incidence. Furthermore, the employment of analog probes determines disturbances introduced by connection cables [18], that represent one of the main problems, due to losses and noise that lie along transmission lines [19]. Therefore, adaptation and conditioning circuits are needed for each probe [20], determining complexity of the measuring system, both for software and hardware level, and a remarkable design work for the choice of the most suitable components. The high number of electronic components determines a complex management of the system.

Nowadays, new technologies based on digital electronic systems allow different solutions for temperature measuring instruments. The employment of digital thermometers solves most of the problems above described for analog solutions, determining cheaper and easier creation and management of the system. In particular, the digital probes selected for the proposed measuring system are the DS18B20, provided by Maxim Integrated. The main characteristics of these probes are: voltage range equal to 3-5.5 V, measurement interval from 218 K to 398 K (-55 °C to 125 °C) with 12 bits resolution, corresponding to increments of 0.0625 K, and an accuracy equal to ±0.5 K. Moreover, digital thermometers can be directly powered through the data line with the Unique 1-Wire protocol and each sensor is univocally identified through a 64 bit code, that is memorized in an internal ROM. The 1-Wire protocol is proprietary and created by Maxim Integrated, and it provides two wires for power and one wire for data bus. Thanks to this protocol, it is possible to connect in parallel many probes, along the same line, in order to reduce the number of cables with respect to analog solutions. These characteristics make digital temperature probes particularly suitable to be used in multi sensors applications, as for instance the hot box apparatus. Moreover, digital sensors are also available with waterproof and moisture-proof properties, allowing also external uses. The general scheme of the designed measuring system is shown in figure 2.
Figure 2. The measuring system architecture.

The system is based on digital sensor interface that allows both data management and signals acquisition. In this prototypal phase, a microcontroller board ATmega2560 has been chosen. The system is equipped with a 20x4 Character LCD Display Module with an HD44780 controller driver to view average temperatures and all error messages, in order to facilitate system debugging without connecting the system to a PC. A card reader permits to save all measured data on a SD memory and it supports up to 32 GB memory device. A real time clock, the low power ds1307 module connected through an I2C protocol, has been also included to keep track of measurements time. Finally, a wireless module was put in order to communicate the data with a remote PC. The software, loaded on the microcontroller, has the capability to manage up to 100 probes through the 1-Wire bus, but with the possibility of extending it with many more probes. In fact, the designed algorithm includes the subdivision of the 10-channel connection as a good compromise for what concerning sensing capability for minimal time sampling and typical application. The probes have an analog-digital converter that converts the read analog temperature values into digital values to be send to the microcontroller by the bus. The maximum conversion time provided by the DS18B20 is 750 ms with a 12 bits resolution. The time requested to start analog-digital conversion and read the measured data is equal to 75 ms and the total time needed to obtain the output is equal to 75 ms. Therefore, this means that each channel has an overall acquisition time of 900 ms, independently of the probes number, because the sensors on the same 1-wire bus receive the data request simultaneously. The designed algorithm has an efficient data management system able to minimize the acquisition time. The proposed algorithm is shown in figure 3.
The proposed algorithm to acquire temperature measurements.

The algorithm is able to recognize and identify automatically the probes really plugged to the system, being not necessary to use the full probes capability in some applications.

The measurement system can be used setting continuous or stepped acquisitions. Measurements data are stored in a 32GB SD card that, considering continuous acquisitions, allows to store data for up to few years.

The total power consumption mainly depends on the acquisition time step and on the number of probes. Without considering the LCD module that is an utility not mandatory for the overall functionality, in the worst case of continuous acquisition the fixed current consumption is 150 mA. Beyond it, the variable component depends on the number of sensors. Each one has a current consumption of 1.5 mA when active and a 0.75 mA when inactive. A more detailed description of the measuring instrument is given in [21].

2.2 Experimental set up

The proposed measuring system has been verified in laboratory, through two different preliminary tests, in dynamic and quasi steady-state conditions. For the dynamic condition a thermoelectric Peltier cell has been employed, while for the quasi steady-state condition, the test was realized in guarded hot box, neglecting thermal analysis of the specimen wall. Both the tests have been carried out with an overall number of the sensors less than the total number usable. The tests have been realized by using n.12 DS18B20, n.4 Pt100 and n.3 T-type thermocouples.

The first dynamic test has been conducted through the use of a thermoelectric Peltier cell (figure 4) to heat up the water contained in a basin, in order to analyze the dynamic response of the digital thermometers under analysis. Initially, the sensors have been maintained at 292 K (+19.0 °C) (room temperature) for about 15 minutes. After this period, the sensors have been immersed for 15 minutes
in the water, previously heated up and maintained at about 328 K (+55.0 °C), thanks to the thermoelectric Peltier cell. At the end of this phase, temperature probes have been taken again to room temperature (292 K).

For this test, the DS18B20 sensors were compared with Pt100 probes.

Figure 4. Thermoelectric Peltier cell.

The second test has been carried out imposing quasi steady-state condition in hot chamber (about 292 K (+19.0 °C)), maintained for about 300 minutes. The digital thermometers response (DS18B20) has been compared with the ones of resistance thermometers (Pt100) and thermocouples (T-type). The setup of the sensors installation has been realized following the standard [11] and the thermal model of the specimen wall interposed between hot and cold chamber (figure 5).

Figure 5. Image of the specimen wall. (a) Visible. (b) IR image with thermal model.

The temperature probes have been positioned according to a matrix scheme on the surface of the sample wall, as shown in figure 6. All the probes have been placed where the hot chamber ensures the best thermal uniformity, i.e. the metering chamber. The digital thermometers have been installed with a horizontal spacing equal to 0.75 m and a vertical distance of 0.50 m. Furthermore, thermal compound has been employed to ensure the mounting between temperature probes and sample wall.
Figure 6. Installation scheme of the temperature probes. Red circles for DS18B20. Blue triangles for Pt100. Green squares for T-type thermocouples.

Both the tests have been carried out with an acquisition time-step equal to one minute. The characteristics of the comparison probes are listed in table 1. The values measured by analog sensors have been acquired through a Delta-T Logger acquisition system.

Table 1. Characteristics of comparison probes.

| Type                          | Measurement interval | Sensitivity |
|-------------------------------|----------------------|-------------|
| Resistance thermometer (Pt100) | from 233 K to 353 K  | 0.4 Ω/K     |
|                               | (-40.0 °C to +80.0 °C) |             |
| Thermocouple (T-type)         | from 73 K to 673 K   | 48.2 μV/K   |
|                               | (-200.0 °C to +400.0 °C) |           |

3. Results and discussion

The first dynamic test shown that in quasi steady-state condition all the temperature probes have similar behavior. When temperature changes, digital thermometers follow temperature variations faster than analog probes, i.e. Pt100, as plotted in figure 7.

Figure 7. Average temperatures for the dynamic test. (A): quasi steady-state condition. (B): dynamic condition (warming and cooling). (C): quasi steady-state condition.
In this case, by comparing values measured by digital and analog sensors, it can be observed a good correlation (figure 8), with a correlation coefficient (R) equal to 0.895 and a coefficient of determination (R²) greater than 0.80. Values hooped in figure 7 highlight that, when temperature changes, the digital probes (DS18B20) have a faster reaction with respect to the analog sensors (Pt100), both in warming (blue circle “1”) and cooling (orange circle “2”).

**Figure 8.** Scatter graph for correlation between digital and analog probes (DS18B20 vs Pt100).

For the second test in quasi steady-state condition, the results obtained show that temperature trend measured by digital thermometers are close to those measured by analog probes, as plotted in figure 9.

![Temperature Graph](image)

**Figure 9.** Average temperatures for the test in quasi steady-state condition.

Also in this case, the comparison between digital and analog sensors highlights a good correlation: the correlation coefficients (R) are equal to 0.805 for the comparison with Pt100 probes and equal to 0.835 for the comparison with T-type sensors (figure 10).
4. Conclusion

In this paper, a new low-cost measuring system based on digital thermometers DS18B20 and on a microcontroller board ATmega2560, is proposed for new applications or refurbishment of hot box apparatus. This system allows to acquire data from high and flexible number of temperature probes, with only one acquisition system. The employment of digital thermometers represents an innovative choice with respect to traditional sensors used in hot box experiments, such as thermocouples and resistance thermometers. This choice allows to achieve advantages for the management of the large number of probes and for the significant reduction in total costs of the instrumentation. Technological reasons, that motivated the creation of this instrument, and hardware and software components have been described.

Preliminary tests have been realized in order to compare digital thermometers with analog sensors traditionally employed in hot box apparatus, such as T-type thermocouples and resistance thermometers Pt100. Two different tests have been carried out. A dynamic test was realized with a thermoelectric Peltier cell to heat up the water contained in a basin, in order to analyze the response of the digital thermometers under analysis. A further test was carried out in hot box. Temperature probes
have been installed on the surface of the specimen wall and quasi steady-state condition has been imposed. Both the tests have shown good correlation between digital thermometers and analog sensors.

Therefore, the proposed measuring system could represent an opportunity for those who want to realize or revamp a hot box apparatus. Future development of the proposed system will concern the possibility of implementing a control system of the temperature actuators in hot box, i.e. electric resistances and refrigerating unit.

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