THERMAL COMFORT PHYSIOLOGICAL EVALUATION: WHICH SENSORS FOR THE MOST ACCURATE ASSESSMENT?

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ABSTRACT

In the field of thermal comfort of garments, the importance of the small air gap between skin and garment, called microclimate, is recognized by predictive models and experimental works. However, accurate measurements of microclimate is complex because its volume is small and variable. Moreover, due to body movement, involuntary contact between sensors and skin/garment strongly affects the measurement. In this work, a wearable device designed for measuring microclimate and skin temperature and humidity is presented and validated through tests in a controlled climatic chamber.

Key Words: THERMAL COMFORT, TEMPERATURE, HUMIDITY, SENSOR, MICROCLIMATE

1. INTRODUCTION

Thermal comfort is a key design parameter for sportswear intended for extreme environmental conditions and intense physical effort. In the literature [1-2], several authors focused on the experimental assessment of thermoregulatory response of human body during sport activities. However, measurement of thermal strain is not straightforward. Several researches highlighted the importance of the small air gap between skin and garment, called microclimate. Accurate measurements of microclimate is complex because microclimate volume is small and variable. Moreover, due to body movement, involuntary contact between sensors and skin/garment strongly affects the measurement. The air gap entrapped in between clothing layers is a good thermal insulator and humidity buffer. However, when sweating, microclimate volume is quickly saturated with vapour, reducing progressively rate of sweat evaporation and, consequently, evaporative cooling. In the literature, it was reported that thermal insulation increases linearly with air gap as long no convection is present [3] and recently simple equations to predict effective insulation of the clothing assembly as a function of microclimate volume were proposed [4]. However, static or dynamic conditions determine completely different scenarios: while microclimate is approximately stagnant or slightly recirculated by natural convection in static condition, in dynamic one, body movement induces forced convection through the clothing. Therefore, thermal insulation is no longer linearly dependent on microclimate volume but it shows a complex behaviour with an optimal volume for best thermal insulation. Beside volume, air gap qualification in terms of temperature and humidity provides valuable information about the mechanisms of heat exchange between body and environment and consequently about thermal comfort. Sportswear designers would benefit of a clear picture of microclimate dynamic behaviour in different environmental conditions, as convective heat flux in the microclimate can be either desirable in case of hot weather or undesirable in extreme cold weather.

Several works explored the field of innovative sensors for skin temperature measurement based on flexible electronics and conductive nanocomposite [5,6,7] but no specific research has been carried out about devices able to monitor microclimate. Due to low thermal capacity, air temperature can undergoes large fluctuations and sensors must be quick enough to respond to these fluctuations. In this work, a wearable device designed for measuring microclimate and skin temperature and humidity is presented and validated through tests in a controlled climatic chamber. The aims of the work are: (1) defining the best experimental setup for reliable measurements of microclimate air gap; (2) developing a system for simultaneous measurements of skin and microclimate temperature.

2. EXPERIMENTAL SETUP

The system developed in this work was a wearable device for measuring humidity and temperature of microclimate and skin in several body districts simultaneously. The system is based on a Microchip microcontroller (ATSAMD21G18) hosted on a commercial development board. The board also embeds a LoRa (Long Range) radio system working around 900 MHz which is able to establish a communication link up to 2 km.. The microcontroller board is miniaturized (51 mm x 23 mm x 8 mm, weight 5.8 g) to guarantee minimum obstruction and ergonomic comfort during use. Power is supplied by a rechargeable lithium polymer battery having 500 mAh capacity. The battery duration is approximately 18 hours. The board hosts both analog and digital sensors: four thermistors (for skin temperature measurements) and two types of digital temperature-humidity sensors: SHT31D (Sensirion) and BME280 (Bosch). The aim of having different sensor types is the comparison and, in perspective, the selection of the best technology for physiological measurements.

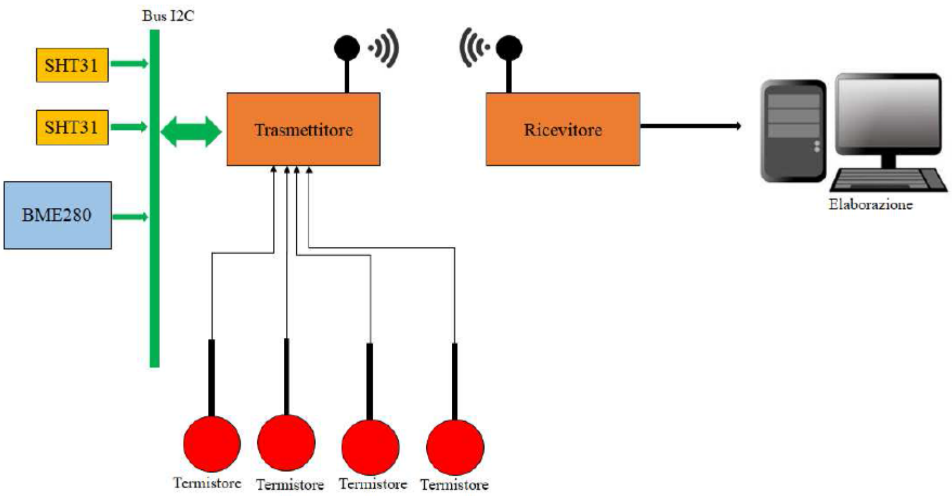
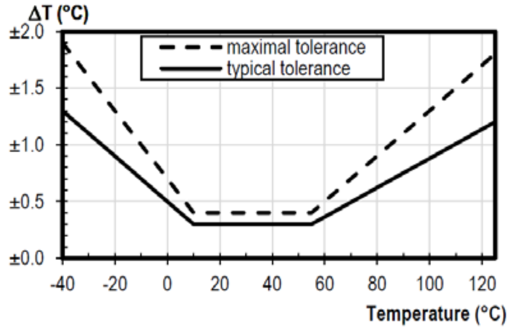


Figure 1. Scheme of the system

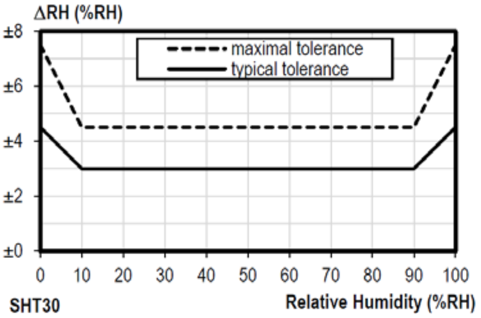
Specifications of the sensors are given in Table 1. Sensor accuracy at extreme temperature and humidity is a key factor for reliable physiological measurements. As shown in Figure 2, for SHT31D sensor as example, while physiological temperature is highly accurate and errors are expected to be lower than 0.5°C, humidity measurements can be an issue in case of high intensity activity with abundant sweating since humidity can be higher than 90%RH .
Considering the specific application of microclimate monitoring, a sensor holder shaped as a PLA cage was designed and 3D-printed with the aim of avoiding fortuitous contact with the skin/garment and at the same time allowing air circulation through the case. Each case hosts one digital temperature-humidity sensor and more cases can be connected in series on the same wire, so that a detailed mapping of physiological data can be obtained. For instance, average skin temperature is the result of a multilinear formula with the temperature of four, eight or fourteen skin districts measured simultaneously, according to ISO 9886:2004.

Table 1. Specifications of the digital temperature-humidity sensors

Sensor	Operating range and accuracy (in brackets)	
	Temperature	Humidity RH
SHT31D	+5°C/+60°C (±0.2°C)	20-80% (±2%)
BME280	-40°C/+85°C (±1°C)	0-100% (±3%)



(a)



(b)

Figure 2. Tolerance of the temperature and humidity SHT31D sensor [SHT31D Datasheet]

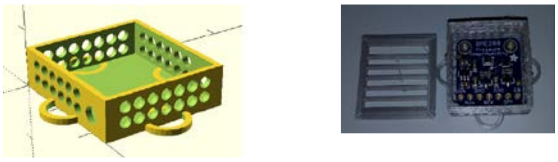
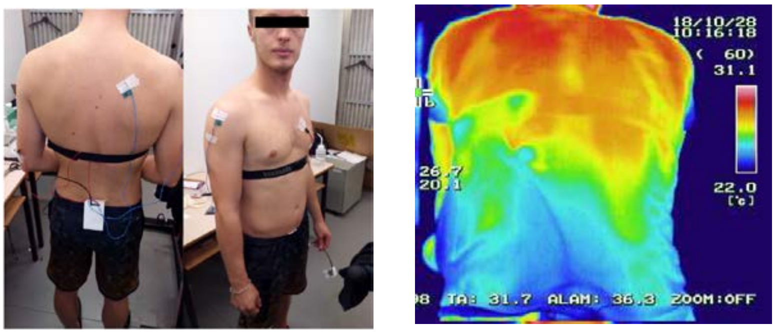


Figure 3. 3D-printed sensor holder.

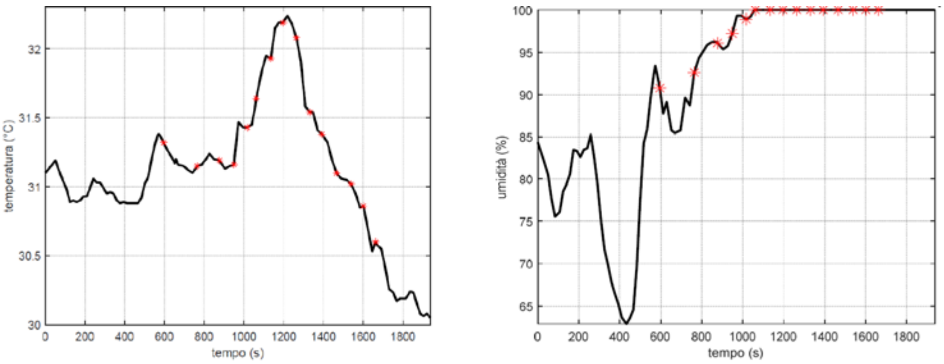
The prototype system was tested inside a climatic chamber (air temperature 23°C, 50%RH) by an athlete who carried out an incremental activity on a cycloergonometer. During the test, the athlete abundantly sweated and the test duration was 31 minutes. Conconi test [8], consisting of increasing power output of the athlete progressively above his/her anaerobic threshold, was carried out: this test can be used to have a rough indication of anaerobic threshold as it is known that heart rate vs power output shows a sudden slope reduction above anaerobic threshold. Blood lactate concentration was measured by Lactate Pro 2 system on a blood drop withdrawn from forefinger. Two SHT31 sensors were placed on the lumbar area and left hip, BME280 sensor was placed on the chest and four thermistors was placed on scapula, deltoid elbow and upper chest, as shown in Figure 4. Then, the athlete wore a polyammide t-shirt with a normal fit (neither loose or tight) so that some air circulates under the t-shirt during physical activity. The garment surface temperature of the back area was measured during the test via Thermocamera NEC G100ex (320X240 pixels, 0.04°C accuracy).



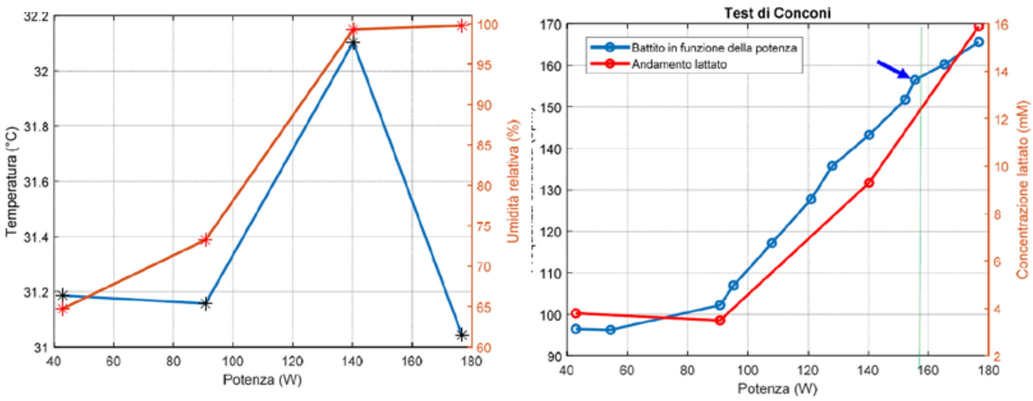
(a) (b)

Figure 4. Receiver and sensors placed on the body (a) and thermal image of the back during the test

Some results are reported as an example. The microclimate temperature and humidity concerning the hip area, as measured by SHT31, are shown in Figure 5. The red stars show the time when the power output was increased by approximately 10 W. Microclimate temperature and humidity increased with power output.



(a) **(b)**



(c) **(d)**

Figure 5. Microclimate temperature (a) and relative humidity (b) of hip area measured by SHT31 as a function of time and power output (c); heart rate and blood lactate concentration as a function of power output (d)

Temperature and humidity stayed rather stable below 100 W, then started to rise steeply. Microclimate humidity was saturated at 140 W, which corresponded to maximum microclimate temperature as well. Copious sweating generated effective evaporative cooling and microclimate temperature fell below initial values at the maximum power output. By comparing the surface temperature recorded by an infrared camera (see Figure 4b) and microclimate temperature in the same area, a temperature difference of approximately 6-8 °C was observed. Such a great difference could be partially due to temperature difference at the measurement sites, but it is also due to the relevant thermal resistance of the sensor holder. This result suggests a conductive material for holder manufacturing would be advisable for more reliable microclimate measurements.

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