Monitoring of temperature stress during firefighters training by means of RFID epidermal sensors

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***Abstract*—Monitoring body temperature is a fundamental health issue for workers that, like firefighters, are sometimes exposed to high thermal stress. Wireless epidermal sensors are a non-invasive tool to collect temperature data in a very efficient way. This paper describes an experimental study carried out during a Compartment Fire Behavior Training. We used wireless thermometers based on Radiofrequency Identification (RFID) technology to measure firefighters clothing layers temperatures. Such devices can be placed directly on the skin like a plaster and are compatible with the UHF RFID standard. Thanks to the simplicity of sensor activation and data download, we managed to obtain multiple data from 10 firefighters during their training. These collected data give an idea of the thermal load that the firefighters experience while performing their duties.**

***Index Terms*—Radiofrequency Identification, Compartment Fire Behavior Training, Firefighters skin temperature, Wearable temperature sensor.**

I. Introduction

While handling emergency situations, firefighters are often exposed to extreme conditions that are related with high physical and thermal loads. The metabolic heat raised by physical activity, the exposure to radiant heat from flames and the interaction with heavy personal protective equipment (PPE) that increases the retention of body heat, produce a not negligible heat stress [1]. High heat stress can lead to physiological and thermoregulatory strain and to an increased risk of physical injuries and illness [2]. Accordingly, monitoring temperatures and heat increases in firefighters is a health and safety priority.

The effect of typical firefighters tasks on their thermo-physiological response [3]–[7] or on their cognitive performances [8], [9] have been investigated to establish thermal exposure limits, improve PPE comfort and safety and to increase firefighters awareness about the way they have to perform their tasks.

Given the exceptional nature of firefighters activities, like suppression of fires, rescuing for victims in hostile environments or handling dangerous substances, they need to be properly trained in realistic scenario simulating the effective conditions in which they have to operate. At this purpose, the Compartment Fire Behavior Training (CFBT) program [10] aims to increase knowledge on the dynamics of fires and on the appropriate protocol to manage events and to increase firefighter safety. Currently, only the environmental temperature is monitored, while the firefighters behavior is supervised by instructors and by the means of video cameras that record the training. In this scenario, sensors for skin temperature measurement could therefore provide an excellent tool to extract a great amount of information about heat exchange from each firefighter.

A simple and inexpensive way to measure skin temperature is with thermistors and thermocouples. However, these sensors are wired connected to the measuring device that has to be worn on the body. A wireless system is indeed required to achieve a satisfactorily comfort and not to burden on firefighters activity. Devices with Bluetooth data link can be a possible low-power option, however, when the communication is expected not to be between only two devices but between a monitor and many sensors, RFID technology is definitely more efficient.

Recently, the authors proposed an epidermal, small-size flexible tag for temperature measurement over the user skin [11], [12]. These devices have been already experimented for fever [13] monitoring. In this work, we proposed the use of this technology for the continuous monitoring of skin temperature of a team of firefighters during a CFBT, both to investigate the insulating performances of PPE and to supervise the thermal load experimented by firefighters in a minimally invasive way.

Fig. 1. Steel containers for CFBT at "Operational Training Center at Montelibretti" (VT, Italy).

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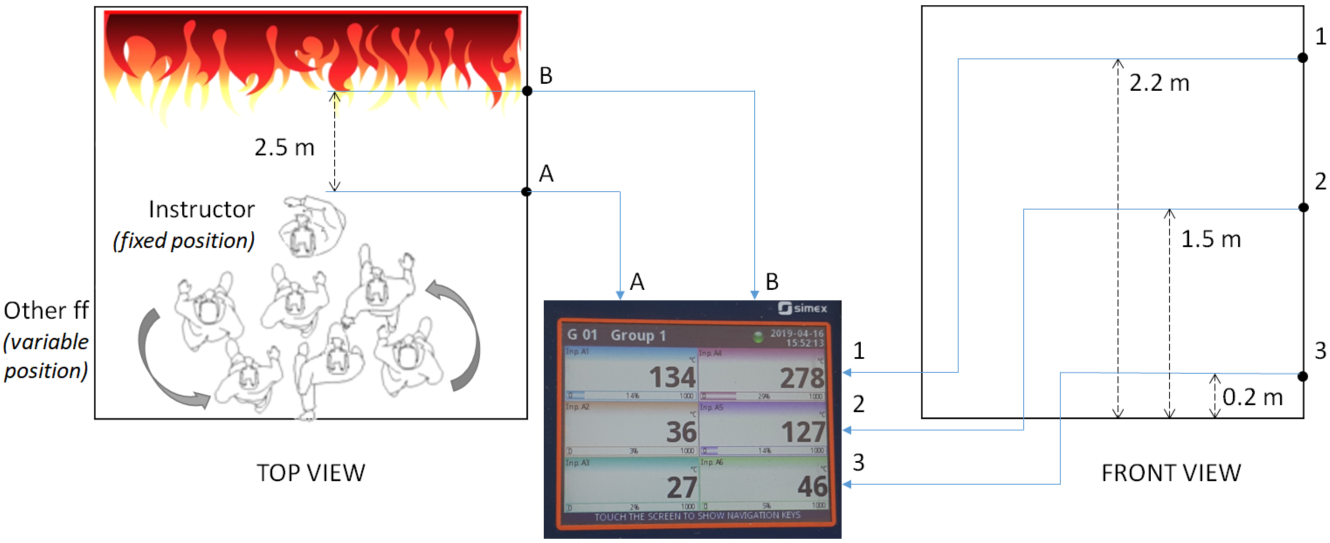

Fig. 2. Containers for the emulation of compartment fire and position of firefighters. Monitoring thermocouples are placed at points A and B at three different heights.

II. Operative scenario

A. Firefighters training

The CFBT was carried out using two steel containers[1] where fire was simultaneously set by using wood-based fuel. The containers are able to realistically reproduce the features of a compartment fire (Fig.1). Once the fire was established, the firefighters, equipped with their PPE, came inside the containers and stayed there for about 20-25 minutes. During this time, the firefighters were allowed to closely observe dangerous phenomena such as flashover, rollover or backdraft, and to study the fumes and combustion gases. Except for the instructors, who maintained a fixed position between the burning fuel (at a distance of about 2.5 m) and the other firefighters, the staff moved around in order to allow everyone managing the water jet and natural ventilation and to learn the correct techniques. During the training, the environment temperature was monitored by six thermocouples placed at fixed points in the containers: three of them in proximity to the burning fuel at three different heights and the other three near the instructors position (Fig.2). A video camera was also present to remotely control the training.

When the training was over, firefighters went outside the containers and began the cooling operations, starting from undressing the PPE.

B. Personal Protective Equipment

The firefighters wear different types of protective clothes as they have to be protected in different body parts (Fig.3). A helmet prevents head injuries and is designed to cover maximum head area while providing a wide range of vision. Helmet allows flames contact but for few seconds and is capable to maintain T$\leq$25°C for 6 min at head level if radiant heat flux is $\sim$7 kW/m^2. A flash hood protects hears, neck and part of the face. It is made by fire-resistant fibers-based fabrics and covers the skin. Often it is designed to accommodate specific respiratory mask that is linked to the self-contained breathing apparatus (SCBA).

[1]Training plant of Italian Firefighters at Montelibretti (VT).

Fig. 3. Firefighter with turnout gear (left) and with overcoat and SCBA (right).

In general, firefighters wear two different types of thermal protective clothing, “intervention uniform” and “heat protection turnout gear”. The first one is the staff garment without fire protection function, comprising a shirt, a jacket and pants. The second one has to be worn over the intervention uniform during any emergency when a firefighter is called upon. It is required that the turnout gear should possess high protective and comfort performances to provide adequate safety to working firefighters in a fire accident. It comprises a coat, a hood and over-pants. The air layer trapped in between the two clothing could enhance the thermal insulation capacity of the overall PPE. Moreover, an overcoat is worn over the turnout gear.

Finally, specific gloves and boots are worn to protect hands and feet.

III. Wireless body sensor network

A. Epidermal datalogger

The dataloggers for skin temperature measurements are derived from [11], [12]. They are small-size flexible tags (Fig.4) communicating in the UHF band (860-960 MHz), and integrating a sensor-oriented IC (SL900A from AMS [14]). This IC provides a native internal temperature sensor (20°C<T<120°C, resolution $\Delta T = 0.1$°C) and a 10-bit ADC for sampling external capacitive and resistive sensors. Its architecture is suitable to both battery-less and battery-assisted passive (BAP) operations mode. In BAP mode, it enables measurements and data storage (841 samples) even in absence of a continuous interrogation by a reader. The antenna layout coupled to the IC is an open loop geometry of external 3 cm x 3 cm size whose shape is adjusted in order to put the vertical surface currents in phase thus maximizing the electromagnetic radiation. The tag was coated with an ultra-thin biocompatible film (Tegaderm, 22 μm thickness) for sanitary reason and placed between two stripes of Fixomull to create an adhesive layer that can be attached on the skin. The expected read distances in BAP mode, by assuming an EIRP=3.2 W (EU), is 1.4 m, that is suitable to an automatic data download as the firefighter walks across a gate equipped with an interrogating module.

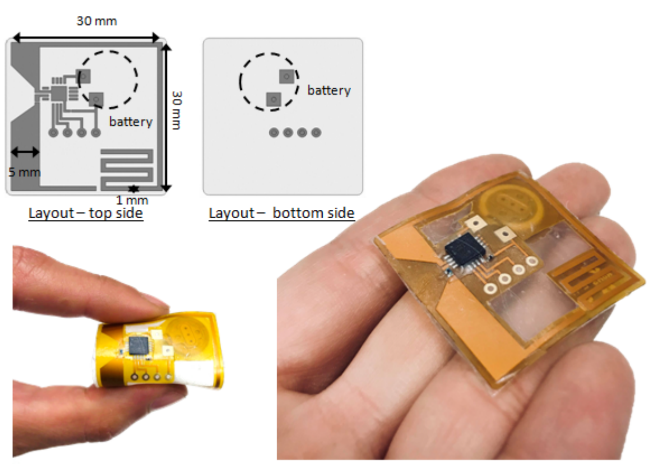

Fig. 4. Layout and top view of the RFID epidermal sensor board with battery.

For the test, 30 tags in BAP mode (for data-logging) have been used. For minimally impacting on training procedures, tags have been first activated and then positioned on 10 firefighters as described in subsection III-B. The sampling time was set to 6 s to cover the required training task.

Before and after training, the tympanic temperatures have been taken from sampled firefighters by means of Braun ThermoScan Pro 4000.

B. Epidermal dataloggers placement on the firefighters

Since the skin temperature is expected not to be uniform, each firefighter was equipped with three tags to monitor at least three spots on the body. For 9 firefighters the three tags were placed as in Fig.5A, i.e. one under the helmet, one on the chest and one on the leg. This arrangement of dataloggers is hereafter referred as “standard”. Since between the helmet and the head there is the flash hood, the sensor is not directly placed on the skin surface as the other two sensors.

For one of the firefighters the three tags have been used, instead, to investigate the insulating performance of PPE. The first sensor was placed on the chest directly on the skin, the second one on the uniform jacket and the last one in the pocket of the turnout gear coat (see Fig.5B); this positioning (referred as “layered”) is a proof of concept that mapping the thermal transmittance through the PPE is possible.

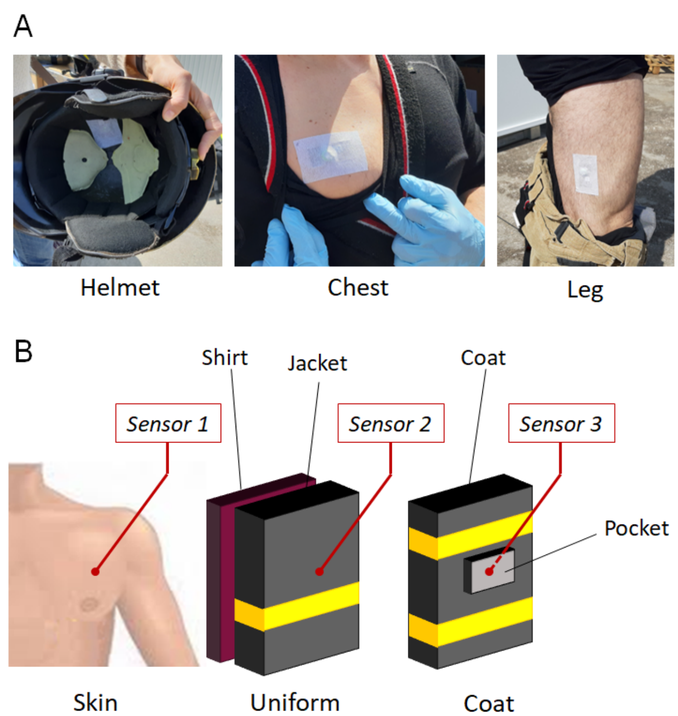

Fig. 5. Placement of RFID dataloggers onto the skin or within the garment. (A) “Standard” datalogger arrangement. (B) “Layered” datalogger arrangement.

IV. Results

An example of measured temperature profiles is shown in Fig.6 and refers to one of the 9 firefighters with a “standard” datalogger arrangement. Approximately 90 minutes of acquisition is visible. The first part of the profile is related to the activity performed before the training, while the time interval in which the firefighter was in the container is highlighted by the shadowed area. Tympanic measurements show a not appreciable increase before and after training. After dataloggers placement and before the training, firefighters worn their PPE and made some trials without fire to test their positioning in the container. The temperature profiles of the chest and of the leg during this time slightly increase, because PPE increases the retention of body heat. Moreover, during these activities before the training, firefighters sometimes have put off and on their helmet, causing respectively a cooling and a heating of the sensor. Therefore, in recorded temperature profiles there can be some specific patterns describing particular activities.

During training period, the temperatures of the helmet, the chest and the leg increase, consistently with the fact that the burning fuel makes the container temperature rise till 90°C in the proximity of the instructors at the end of the simulation. All measurements on the skin (chest and leg) never exceed 41°C (Fig.7A), therefore always below the critical value (43°C) at which breakdown of tissues starts [7]. However it is conceivable that, if the training had been longer in time, the temperatures could have increased, thus monitoring skin temperatures can become mandatory to settle a more safety and accurate protocol for training.

It is worth noticing that the PPE stores some amount of thermal energy due to its heat capacity. Such a stored energy releases during the cooling phase after the training and causes increase in sensors temperature even after the exposure.

The highest temperature was recorded under the helmet. Fig.7A shows the maximum temperatures measured in each body district for all the firefighters. Helmets reach temperature of about 50-55°C. For one of the firefighters the helmet temperature even exceeds 60°C. In spite of these values are not representative of the head temperature, due to the flash hood between sensor and head, they give information about the extent of thermal load that is in close proximity to it. Direct skin temperature values (chest and leg) are far lower than the ones on the helmets, but however not negligible. The mean maximum temperatures on the legs (37.8 ± 1.0°C) are slightly lower than the ones on the chest (39.2 ± 0.8°C), due to the vertical spatial temperature gradient of the container.

Fig.7B summarizes the temperature rise due to fire exposure on the three body districts (helmet, chest and leg) for the 10 firefighters. Highest increments are for the helmets (22.8 ± 7.7°C), while skin increments are far lower, with slight differences between chests and legs.

Finally, Fig.8 shows the temperature profiles obtained on the firefighter with tags "layered" arrangement. When the simulation starts, the inner sensor records the highest temperature, confirming that the PPE limits heat exchange rate with environment, thus increasing the degree of physiological strain so that skin temperature is already high before being directly exposed to fire. When the heat flux from outside becomes greater than the one from the body, the most external sensor starts to record the highest temperature. The higher the temperature in the container, the higher the difference between the temperature recorded on the external turnout gear coat and the one on the jacket, proving the high thermal protective coat performances. If the heat flux exchange is known, a map of thermal transmittance of different layers could be derived, and accordingly the thermal insulation of PPE (that can be affected by many factors) during a training could be estimated.

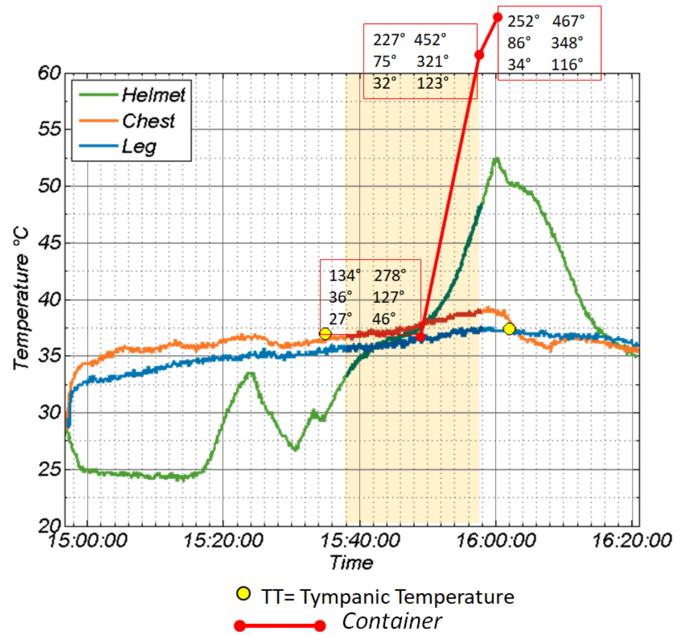

Fig. 6. "Standard" dataloggers arrangement: temperature profiles measured on the helmet, the chest and leg of a firefighters. Shadowed area refers to the time interval in the container. The red insert show the container temperatures measured by the six thermocouples: three near the instructor (first column) and three near the fuel (second column).

V. Conclusions

Preliminary tests of continuously monitoring the skin temperature of firefighters during their CFBT have been presented by using wireless RFID technology. The epidermal dataloggers, that are cheap, small-sized, flexible and skin conformable, have been demonstrated reliable, easy to manage and, mostly important, they haven't given any hindrance to firefighters activity.

This proposed technology could be improved by adding other sensors (like humidity, pH) to combine different physiological parameters profiles. Monitoring different parameters can be the starting point to develop analysis models both for the activities performance analysis and for firefighters health, gaining a more comprehensive insight to thermal stress and hazards in firefighters activity.

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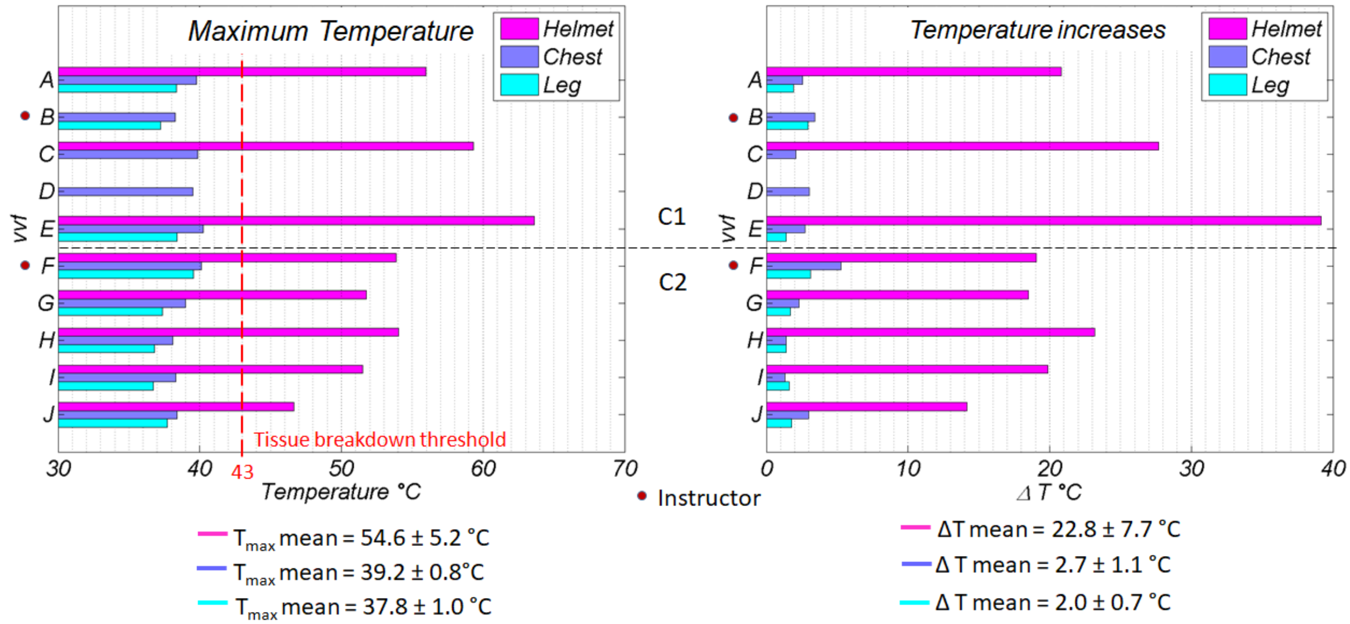

Fig. 7. (A) Maximum temperatures recorded on the three body districts (helmet, chest and leg) for the 10 firefighters. (B) Temperature increases due to fire exposure on the three body districts (helmet, chest and leg), evaluated as the difference between the maximum temperature recorded and the temperature at the starting time of the simulation. Red dots near the letters indicate the instructor.

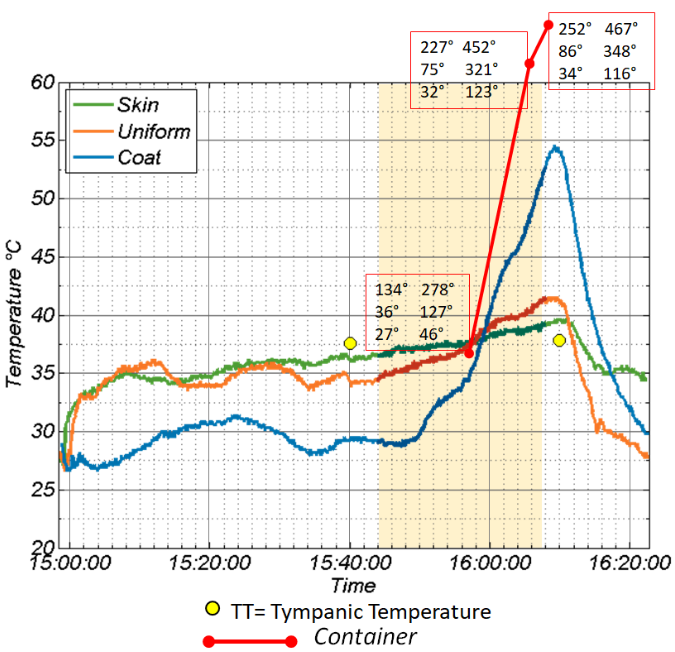

Fig. 8. "Layered" dataloggers arrangement: temperature profiles measured on the skin, on the uniform jacket and in the pocket of the coat of the firefighter. Shadowed area refers to the time interval of the simulation in the container. The red insert show the container temperatures measured by the six thermocouples: three near the instructor (first column) and three near the fuel (second column).

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