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Thermal parameters measurement on fire fighter: improvement of the monitoring system

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Abstract—**Real time monitoring of the thermal parameters on firefighter when operating is one of the ProeTEX project goals. The newly developed equipments in the framework of this project, integrate one temperature sensor and one heat flux sensor in the rescuer's outer garment. The environment in which firefighters operate is dangerous and the thermal risks can occur everywhere. Consequently the heat flux is so not necessarily symmetrical. To improve the thermally at risk situation detection, a modified platinum sensors array was integrated in the jacket in order to monitor simultaneously heat flux and temperature surrounding the rescuer. The sensors were placed in the most exposed area (shoulders and chest) to monitor thermal parameter in different directions. The heat flux is calculated from the temperature difference. This sensors array enables the detection of temperature increases and heat flux even when the heat source is localized on one side.**

I. Introduction

ProeTEX is a European Integrated Project (Project FP6-2004-IST-4-026987, [1]) whose goal is to develop instrumented equipments for rescuers in order to improve their safety, their coordination and their efficiency. These new protective clothing integrate sensors to monitor physiological and ambient parameters such as heat rate, core temperature, respiratory rate external temperature, posture, etc. GPS, acquisition and transmission modules are also integrated into the garments [2], [3]. These sensors are integrated into the jacket and the t-shirt intended to the civil security personnel and firefighters. Fire-fighting imposes heat stress as show in several studies held in Canada [4], [5] and in Scandinavia [6], [7]. A previous paper on this project [8] showed the importance of monitoring thermal parameter on firemen during fire exposure and fire attack. In this study it was point out the necessity to replace sensors in the most exposed area: the shoulders.

In this paper, improvement brought to the monitoring system in order to make thermally at risk situation detection stronger are presented.

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Figure 1: sensor integration in the firefighter jacket. A) Platinum sensors were located on the left and right shoulders and on the chest. B) The modified platinum probes were integrated on each side of the thermal insulation layer, between the comfort layer (green) and the external layer (blue).

II. Materiel and Method

A. Temperature Sensors

The platinum sensors [9] used are Pt1000 platinum resistors. The nominal value of the Pt1000 probes is 1000 Ω at 0°C. These sensors are Positive Temperature Coefficient (PTC) thermistors, i.e. their resistance value increases with temperature and could be used for temperature ranging from -70°C to +500°C. Relationship between temperature and resistance is given by the equation:

$R(T) = R_0[1 + AT + BT^2 + C(T - 100)T^3]$ for the range -70°C to 0°C

$R(T) = R_0(1 + AT + BT^2)$ for the range 0°C to 500°C

With R_0 the resistance value at 0°C, here 1000Ω
T the temperature in °C
$A = 3.9083 \times 10^{-3} °C^{-1}$
$B = -5.775 \times 10^{-7} °C^{-2}$
$C = -4.183 \times 10^{-12} °C^{-4}$

The Pt 1000 resistors were welded on a 2 cm diameter Kapton® circular foil. The sensitive part of the platinum sensor was in contact with a 1 cm diameter copper circle to improve the thermal exchange between sensor and environment. The sensors were the encapsulated with a resist to improve their mechanical resistance. The advantage of these modified platinum sensors is their small size, due to the small size of Pt1000 probes used, with a surface of about 3.14 cm² (against 19.63 cm² for heat flux sensors used for the reference measurement for example [13]). This enabled an easier integration in the jacket.

With that measurement method, sensors are used to measure both temperature and heat flux whereas with heat flux sensor, temperature is not available. The price of the sensor is also an advantage (about 140 times cheaper).

B. Sensors integration

The outer garment is composed of three layers: the external layer, the thermal insulation (in Gore-Tex®) and the internal layer (also called comfort layer). The platinum sensors were integrated on the thermal insulation (Figure 1):

- Three sensors were positioned on the upper face, towards the external layer. They were located in the left and right shoulder area and in the chest area and were used to measure temperature of the external layer of the jacket, varying as the external temperature.
- Two sensors were positioned on the lower side, towards the comfort layer. These sensors were placed in the left and right shoulder area symmetrically to the previous sensors with respect to the thermal insulation layer. They were used to monitor heat flux by temperature difference.

If inner face temperature is higher than external face temperature, heat flux is positive. The wearer loses heat. This is the "normal" case. The metabolic heat (basal and physical activity) is lost.

If the inner face temperature is lower than external face temperature, heat flux is negative. Heat passes though the insulation layer and heated the wearer who cannot remove his metabolic heat production. This situation is potentially risky if prolonged in time.

C. Acquisition module

An acquisition card has been developed to enable the monitoring of temperature and heat flux. This card is based on PSoC[TM] (Cypress, Inc.) technology [10] (Figure 2). This component, composed of an 8-bit Harvard architecture microprocessor, enables reducing the acquisition system size thanks to the programmable analog array and programmable digital array [11]. Therefore the signal conditioning, signal processing and communication are realized within a single component. The RF transmission is based on Zig-Bee technology by using a XBee® module (Digi, Inc.) [12].

Temperature was acquired with the platinum resistors. The signals were first linearized by means of a Wheatstone bridge. Then they were multiplexed to only use one amplifier and one analog-to-digital converter. The acquisition frequency was set at 8 Hz. For each temperature sensor, the 8 ADC data were averaged and the frame was built with these five ADC averages. Then the frame was transmitted to a computer (1Hz) via the X-Bee module.

A software processing was the applied to the ADC values to convert them in temperature values. The heat flux was

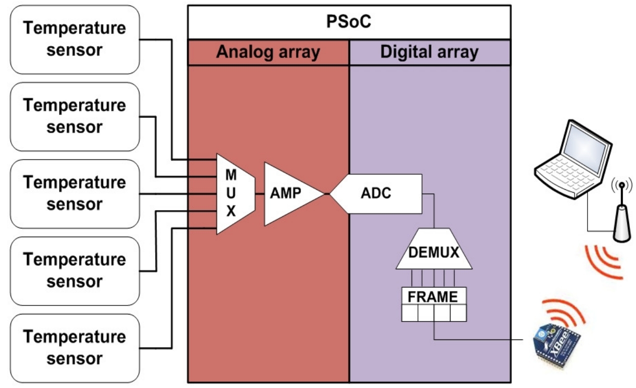

Figure 2: acquisition system architecture based on a PSoC[TM] programmable component.

also calculated during the software processing.

D. Comparative test

Laboratory tests were carried out to compare the measurement obtained with the acquisition module developed and reference measurement.

The reference instrumentation was CAPTEC ENTERPRISE® [13] heat flux sensor and a commercial acquisition system from OMEGA® [14]. The heat flux sensor was place on the thermal insulation layer, towards the comfort layer, in the in the right shoulder area, near the platinum sensors.

To perform the test, a mannequin, equipped with the outer garment, was exposed to a right shoulder oriented heat flux. The heat flux was simulated using an infra-red emitting bulb (power: 250W). The mannequin was oriented three-quarter face from the IR source.

The temperatures and heat flux were recorded during 15 minutes and 10 seconds. Heating phase by IR source and cooling phase when IR is turned off were recorded.

E. Comparison method

To make the comparison easier between the two signals, normalized heat flux were calculated as follow:

- For the reference measurement:

$$HF_{norm} = \frac{HF}{|HF|_{max}}$$

With HF the heat flux, in W/m²
$|HF|_{max}$ the maximum absolute value of heat flux, in W/m²

- For the platinum sensor method:

$$HF_{norm} = \frac{\Delta T}{|\Delta T|_{max}}$$

With ΔT the temperature difference between the two thermal insulation layer's faces, in °C
$|\Delta T|_{max}$ the maximum absolute value of temperature difference, in °C
And $\Delta T = T_i - T_e$

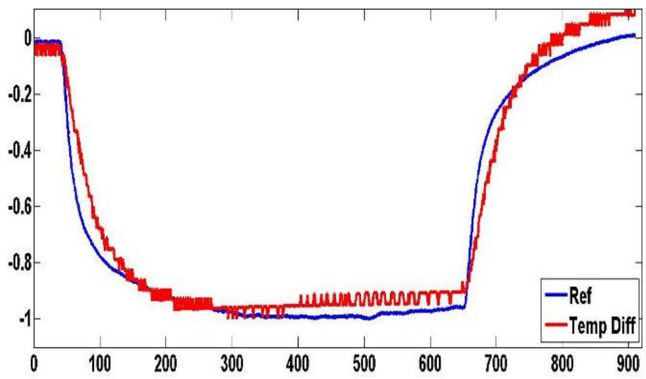

Figure 3: comparison of the two normalized heat flux, the reference in blue and the calculated heat flux (by temperature difference) in red.

Where T_i is the temperature of the inner face of thermal insulation layer and T_e is the temperature of the external face of thermal insulation layer.

III. Results – Discussion

The aim of the test carried out was to validate the new measurement method by comparing the two heat flux signals (curve shape, response time) and to show improvement provided by the redundancy of temperature sensors.

A. *Results of the test*

The two normalized heat flux were shown on Figure 3. The two curves have similar shapes. When the IR bulb was turned on, the reference measurement and the differential temperature heat flux measurement decreased simultaneously. They reached a plateau at the same time and this situation lasted about 450 seconds in each case. However, the differential heat flux sensor, based on the platinum resistors, had a higher thermal capacity, due to the thermal insulation layer. The transient states (decrease and increase of heat flux) are a little beat longer with this sensor.

Figure 4 showed the temperature measurements performed with the platinum sensors integrated in the outer garment. The heat flux source directly heated the right shoulder. The right shoulder temperature (red curve) so increased from the ambient temperature (23.2°C) to 40°C. As the IR source is an extended source, the mannequin's front was also heated. The chest temperature (purple curve) increased of about 2°C, whereas left shoulder temperature (green curve) remained stable during the test.

B. *Analyses*

The two signals were highly correlated (correlation coefficient equal to 0.9872). So the measurement method based on temperature difference could be considered correct.

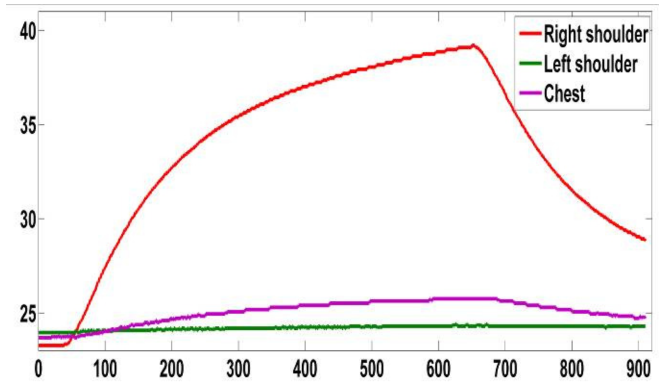

Figure 4: temperature recording in the outer garment on right (red) and left (green) shoulders and in the chest area (purple) in °C.

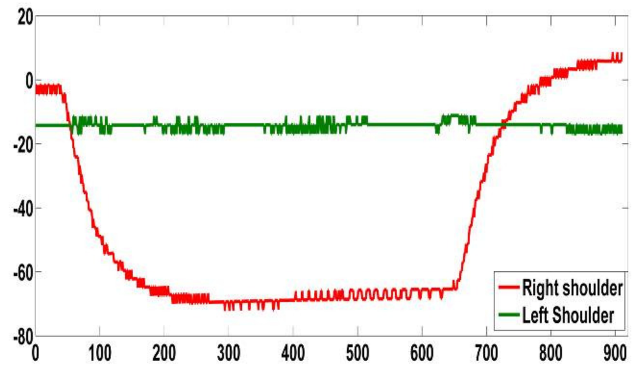

Figure 5: heat flux calculated by temperature difference on right (red and left (green) shoulder, in W/m².

This result also enabled the calculation of thermal resistance of the differential heat flux sensor. It was composed of the complex assemblage in series of copper-Kapton-GoreTex-Kapton-copper. To evaluate this thermal resistance, the following calculation was done:

$$R_{th} = \frac{(T_i - T_e)}{HF_{ref}}$$

With R_{th} the thermal resistance of the differential heat flux sensor calculated before, in °C.m².W^{-1}

T_i the temperature of the inner face of thermal insulation layer, in °C

T_e the temperature of the external face of thermal insulation layer, in °C

HF_{ref} the reference heat flux, monitored with the reference instrumentation, in W.m^{-2}

Differential heat flux sensor's thermal resistance was $R_{th} = 0.0409\ °C\ m^2 W^{-1}$.

To obtain heat flux provided by the platinum heat flux sensor, the temperature difference had just to be divided by this value. The heat flux is then:

$$Heat\ flux = \frac{(T_i - T_e)}{R_{th}}$$

With R_{th} the thermal resistance of the differential heat flux sensor calculated before, in °C.m².W^{-1}

T_i the temperature of the inner face of thermal insulation layer, in °C

T_e the temperature of the external face of thermal insulation layer, in °C

This calculated heat flux was shown on Figure 5.

C. Improvement provided

On Figure 5, the right shoulder heat flux (red curve) was negative due to the entering heat flux on the mannequin when the IR source was turned on. Once the heat source turned off, the heat flux increased. The left shoulder heat flux (green curve), meanwhile, remained relatively stable during the all trail. This is due to the asymmetry of the IR exposure. The right side of the mannequin was exposed to IR whereas the left side not.

This asymmetry was also highlighted by temperature record in Figure 4. Right shoulder temperature increased from ambient temperature to about 40°C, while the chest temperature increased a little (about 3°C) and the left shoulder temperature remained stable.

The sensors array enabled the detection non symmetric thermal risk situation, as show by the increase of temperature and the heat flux variation only on the right side. If the heat source was on the left side, the single sensor integrated in the previous ProeTEX prototype would not have detected the thermally at risk situation.

IV. Conclusion

The sensors array integrated in the outer garment provide a good quality thermal parameter monitoring, with similar response to heat flux sensor. This measurement method has the advantage to use small sized and cheap sensor, compared to heat flux sensor already integrated in the jacket.

The redundancy of sensors – three temperature sensors and two heat flux sensors – enables a better monitoring of thermal parameters. In most cases, heat flow is not symmetrical. This thermal sensors array in the outer garment provides information on thermal risk incurred by the jacket wearer such as entering heat flux or high temperature sources, whatever the heat source location (front, left or right side). There is no sensor in the back for two main reasons:

- The firefighter carries breathing apparatus on his/her back
- The firefighter does not turn his back on the fire

The future of this system is to be test in field trials (urban fire simulation and forest fire simulation) to validate this measurement method in real conditions.

Acknowledgment

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