Flexible Heat Flux Sensor for Firefighters Garment Integration

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ABSTRACT

The interest in using optimal equipment to face unknown hazards is growing, as it ultimately save lives. This holds especially true for fire-fighters which are confronted with other hazards during the course of operations. Improvement of their security by an integrated sensory clothing system was the main objective of the European project ProeTEX. In this context, the integration of commercial heat flux sensors into fire-fighters garment has proved the interest of such measurements. However, low flexibility and high cost remain major disadvantages of these sensors. The objective of this work is to develop an innovative heat flux sensor based on a low cost technology. Heat flux sensors have been realized using printable thermoelectric materials and present high sensitivity ($146 \text{ mV/ (W/cm}^2$)). Their flexibility is compatible with integration in clothes and three specific integrations are proposed and compared. Proof of concept of flexible heat flux sensor is also presented in this paper.

Keywords: Fire-Fighter Application, Flexible Technology, Heat Flux Sensor, Specific Clothes Integration

INTRODUCTION

This work was supported in part by the European Union, in the framework of the Integrated Program ProeTEX (http://www.proetex.org/), which aims at developing integrated sensory clothing system for rescuers in order to improve their safety, their coordination and their efficiency (Bonfiglio et al., 2007; McAdams et al., 2009). If personal protective equipment efficiently insulates body against high stress and harsh environment of an operation, it sometimes results in insufficient perception of normal corporeal sensations and hazard
warnings. Used to measure environmental, physical and physiological parameters, sensors embedded in the clothing are designed to reduce risk and improve emergency response capabilities. In hazard conditions, heat flux sensors in particular should be able to alert fire-fighters of a critical thermal exposition before any heat perception on skin (Oliveira, Gehin, Massot, Ramon, Dittmar, & McAdams, 2010; Oliveira, Gehin, Delhomme, Dittmar, & McAdams, 2009). However the cost and the rigidity of such commercialized sensors are a limit to their integration. The work described in this paper concerns the development of a new generation of flexible heat flux sensors based on printable thermoelectric materials. Thanks to the good resulting flexibility, innovative integrations have been envisaged to have access the heat flux across fire-fighters garment.

**METHODS**

**Concept of Heat Flux Sensors Integration**

Various designs of heat flux sensors exist, such as Gardon gauges, plug gauges, and thin film thermocouple arrays (Gardon, 1953; [7]). Thin film types have the advantage of high frequency response and minimal flow and thermal disturbance [8]. In this case, minimal heat flux perturbation by the sensor integration is of primary importance to ensure a thermal flow measurement identical to the one coming across fire-fighters jacket. All heat flux sensors operate by measuring the temperature difference across a thermal resistance, based on Fourier’s law. In practice, heat flux, \( Q \), is obtained by the finite temperature difference \( (\Delta T) \) across a thermal resistance of the finite thickness \( (\Delta x) \), as shown in Equation 1:

\[
Q = -k \frac{\Delta T}{\Delta x}
\]  

(1)

The heat flux \( (Q) \) is in \( \text{W/m}^2 \), thermal conductivity \( (k) \) is in \( \text{W.m}^{-1}.\text{K}^{-1} \), the temperature difference \( (\Delta T) \) in K, and the finite thickness \( (\Delta x) \) in m.

The temperature difference is conventionally obtained by a voltage measurement on N thermocouples association, called heat flux sensor. n-type and p-type materials are connected with a metallic junction to form one thermocouple. Association of a large number of thermocouples leads to an increase in the heat flux measurement sensitivity. The relation between the voltage, \( U \), and the temperature difference, \( \Delta T \), is given by relation (2). The sensitivity of heat flux sensors is proportional to the thermal resistance, \( R_{\text{th}} \), which allows the temperature difference measurement:

\[
U = N(S_p - S_n)\Delta T = N(S_p - S_n) \times R_{\text{th}} \times Q \times A
\]  

(2)

where \( N \) is the number of thermocouples, \( S_p \) and \( S_n \) in V/K are the Seebeck coefficients of p-type and n-type materials, respectively and \( A \) is the sensor area in \( \text{m}^2 \).

Figure 1 shows the two geometries flexible sensors that have been manufactured in this study. 1) On Figure 1a, the 3D-sensor integrates thermoelectric materials inside the substrate. The heat flux flows through the substrate and its measurement depends directly on the temperature difference (Thot-Tcold) between the top and the bottom of the sensor. 2) On Fig 1b, the 2D-sensor consists in thermoelectric legs deposited on the top of the substrate surface. In this case, the heat flux measurement depends on the temperature difference (Thot-Tcold) between the ends of the thermoelectric legs.

The fire-fighter jacket is composed of a stack of three textile layers separated by an air layer: an external layer, a thermal barrier layer and a comfort layer. Based on the two geometries described above, three integration configurations have been envisaged for the clothing integration (Figure 2).
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