Sensors and Actuators A 235 (2015) 131–139

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Embedded textile heat flow sensor characterization and application

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ARTICLE INFO

Article history:
Received 3 June 2015
Received in revised form 30 September 2015
Accepted 2 October 2015
Available online 20 October 2015

Keywords:
Textile sensor
Heat flow
Moisture transfer
Intelligent textiles

ABSTRACT

Measuring heat flow can be useful in determining the amount of heat exchanged between the human body and the environment in order to improve the comfort, efficiency and sometimes, the safety of the wearer. Scientists use passive heat flow sensors to measure body heat exchanges with the environment. In recent years, several such sensors have been developed and concerns about their proper calibration have been expressed. Moreover, the existing heat flow sensors are impermeable and prevent evaporation which gives inaccurate results when the evaporation phenomenon is present. We developed a flexible heat flow sensor which is permeable to water vapor. This sensor takes into account the evaporation phenomenon and allows a better measurement of the energy during the heat exchange. This paper describes the textile heat flow sensor realization, calibration and possible applications.

1. Introduction

By controlling heat passing through a clothing system it is possible to protect the body against overheating as well as against undercooling. Moreover, measuring heat flow can be useful in determining the amount of heat exchanged between the human body and the environment in order to improve the comfort and efficiency of the wearer. Heat flow is monitored by using heat flow sensors. Heat flow sensors measure the voltage caused by heat flow passing across a thermal resistance using thermocouples. Thermocouples are based on the thermoelectric effect discovered by Seebeck in 1821. In a closed circuit formed of two different metals a voltage flows if the two junctions are at different temperatures. The generated voltage depends on the thermocouple used and the temperature difference between the two junctions. The generated voltage is proportional to the heat flow which passes through its surface. The response is linear and the linearity coefficient is supplied by the manufacturer, i.e. sensitivity in $\mu V/(W/m^2)$. When the heat flow is positive, heat goes out of the body, the subject removes the metabolic heat over-production to avoid internal temperature increase. When the heat flow is negative, heat enters in the body. The subject gets heat from the environment and his core temperature increases [1].

Scientists use passive heat flow meters to measure body heat exchanges with the environment. In recent years, several such sensors have been developed and concerns about their proper calibration have been expressed. The sensors respond differently to the calibration setups and therefore, one overall calibration model is not valid. Therefore, a proper calibration corresponding to the intended purpose of use is required [2,3]. It is also important to report details of the calibration procedure. As the heat flow from the human surface is typically very small, factors influencing the sensor reading, such as thermal resistance, weight, or flexibility of the carrier material have to be considered. It is recommended to use a thin, light sensor with good thermal conductance for human subject studies. However, it is also needed to evaluate these sensors in transient conditions, tested under steady-state conditions are not all the time relevant [2]. A sensor generally refers to a device that converts a physical measure into a signal that is read by an instrument. All sensors have similar fundamental properties defined by sensitivity, range, accuracy, precision, and the need to be calibrated against known reference standards. Another important property is the interaction between sensor and the measured phenomenon [3].

Commercially available heat flow sensors are impermeable and prevent evaporation which gives inaccurate results when the evaporation phenomenon is present [4]. On the other hand, the sensor is a new thermal resistance layer added to the thermodynamic system and consequently changes the heat flow in the measured area.

We developed a new flexible heat flow sensor which is permeable to water vapor. This sensor takes into account the evaporation phenomenon and allows a better measurement of the energy

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http://dx.doi.org/10.1016/j.sna.2015.10.004
0924-4247/

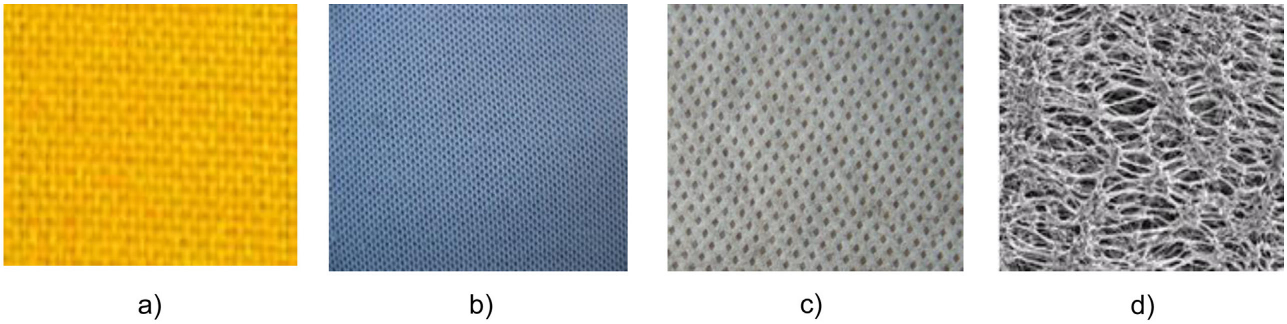

Fig. 1. Examples of fabrics.
(a) woven fabric; (b) knitted fabric; (c) non-woven fabric; (d) PTFE membrane.

during the heat exchange. This paper describes the textile heat flow sensor realization, calibration and applications.

2. Realization of the textile flow sensor

Textile fabrics are flat porous materials which are produced by different textile manufacturing techniques using different fibrous forms of input material (or structural elements), and consequently having different porous structures:

- Woven fabrics are made by interlacing vertical warp and horizontal weft yarns at right angles to each other (Fig. 1a);
- Knitted fabrics are made by interlacing yarn loops (Fig. 1b);
- Non-woven fabrics are produced from staple fibers or filaments by different web-forming, bonding and finishing techniques (Fig. 1c);
- Membranes which are thin, soft materials made from a polymer, that contains a lot of pores with diameter smaller than the water molecule and larger than water vapor molecules; the membranes are often laminated to the fabric to provide properties such as strength, water-proofing or wind-proofing to enhance the performance of the fabrics (Fig. 1d).

The textile heat flow sensor will be integrated into a firefighter jacket to perform the monitoring of the human-environment interface, through monitoring the heat flow. Therefore, the textile substrates used are parts of the overall fire protection assembly. Protective clothing systems consisting of three aramid-based layers (outer shell, thermal barrier and moisture barrier) are typical for firefighters. In firefighting, underwear with the role to provide an additional layer of material between the hazard and the person's skin is used [5] .

Six sensors with a surface of $5 \times 5\,cm^2$ were produced on a textile substrate according to Table 1.

The physical properties (thickness, surface weight, bulk density) and the thermo- physical properties (water-vapor resistance and thermal resistance) of the fabrics were measured and are displayed in the Table 1. Thickness was measured under the pressure of 1 ± 0.01 kPa, according to the standard ISO 5084:1996. Density was calculated from the values of fabric monolayer thickness and surface weight (which was determined using an analytical balance). The average of ten measurements was calculated. Measurements of thermal (R_{ct}) and water-vapour resistance (R_{et}) of fabrics were conducted on the sweating guarded hotplate according to the standard ISO 11092:1993. Specific environment testing conditions prescribed by this standard were met using a climatic chamber [5].

To manufacture the textile heat flow sensors the following procedure was followed:

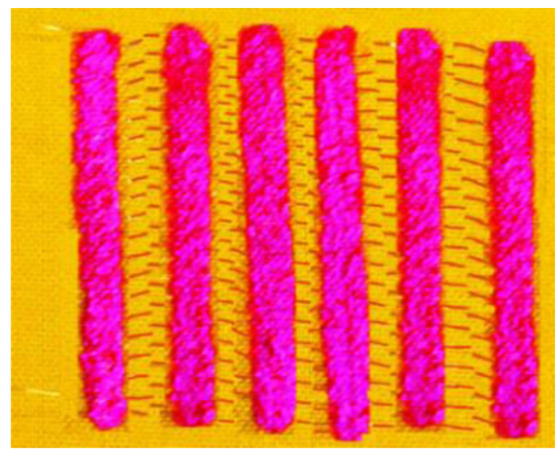

Fig. 2. Treatment with polymer.

- Insertion of a constantan wire (from Omega®: SPCC-005 127 µm diameter) within the textile structure with a float of 5 mm. The sensors having as textile substrate the knitted and the nonwoven fabrics were produced by inserting manually the wire into the structure. For the sensors with the woven fabric substrate, the constantan wire was inserted during the weaving process. The weaving process was performed on a weaving machine Patronic, 24 shafts, with Selectron-MAS-Control.
- Local treatment with polymer (resin) in order to allow the partial copper deposition. For that, resin was deposited on a zone consisting of two half-segments located on both sides of the textile, to protect from copper deposition, (Fig. 2). The resin is resistant to an electrolytic solution.
- Electrochemical deposition of copper on the constantan wire (Fig. 3). The thermo-electrical wire was obtained.
- Post-treatment for polymer removal. The textile flow sensor are shown in Fig. 4.

3. Textile heat flow sensor characterization

All sensors have similar fundamental properties defined by sensitivity, range, accuracy, precision, and the need to be calibrated against known reference standards. These basic properties are important when we design, calibrate, use, and model output data for the purpose of objective physical activity monitoring [3].

Researchers raised concerns regarding the development of a sensor with accurate calibration. Danielsson [6], Ducharme and Frim [7], noted that the calibration technique used greatly affects both the calibration value and the measurement obtained on humans. In addition, Ducharme et al. [8] reported a mean difference of 20 % when comparing the sensitivity delivered by the manufacturer with the authors' own recalibration measurements. In