Heat Transfer Model for Embedded Thermocouple in Firefighter Glove

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Abstract:

Fire fighters wear gloves to protect them from burns or cutting damages. In this work a fast thermocouple sensor has been integrated to measure contact heat. By using an intelligent wireless sensor node inside the glove, measurements have been processed directly to a vibration feedback. This document describes the use of COMSOL heat transfer module as simulation tool for this textile integrated thermocouple. The thermocouple must be placed behind heat protective layers of the glove whereas the reaction time increases. Simulation results show the expected reaction time and the influence of backside coat inside the glove. The results have been compared to measurements.

Keywords: thermocouple, textile sensor integration, heat convection, firefighter glove

1. Introduction

Firefighters wear gloves to shield them from burns or cutting damage. In the line of duty sometimes they have to know if there is a fire behind the door before they enter a room. In this case they undress one glove to feel with the back hand the temperature of the door. This procedure takes rescue time and unprotects them because of undressing.

In this work, a textile integrated thermocouple has been developed to measure this contact heat. It is placed on a stiff-flex circuit board as a part of an intelligent sensor node (fig. 1). This node communicates wireless whereas an acceleration and resistive temperature sensor are integrated for gesture recognition and inner temperature measurement. The whole sensor node concept is well described in [1]. All feedback recognitions have been done by using a vibration motor. Because of the EN659 standard [2] for fire fighter gloves, the thermocouple couldn't be placed on top of the glove while penetrating the glove membrane to ensure a measuring device behind the membrane. For this reason the thermocouple had to be placed together with the rest of electronics behind the membrane. In this case, the glove offers a high radiation heat and heat measurements can only be done by contactacting with a specific outside of the glove where the thermocouple lays under. Creating a heat contact with the protective glove leads to heat convection though the protective membrane that is much higher than the heat radiation. The presented model assumes a local contact heat for measuring with the thermocouple. Radiation heat influences the whole glove nearby equal and is measured by the inner temperature sensor.

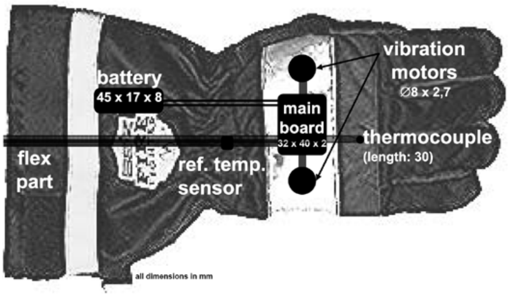

Figure 1. Schematic model of the sensor node [1]

Because of high protection, the heat need some time to reach the thermocouple while contacting a heat device. This time should be as small as possible to guarantee a fast and accurate contact measurement. Recognition of heat measurement is directly processed inside the glove and transformed into a vibration signal. The Forecasting of the time constant leads to the practical implementation inside the glove. Simulations with COMSOL show the influence of heat capacity and conductivity of different materials inside a schematic model of the firefighter glove. Furthermore different thermocouple types and material thicknesses have been simulated for practical implementation.

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2. Implementation Methods

The simulation model offers a replicable geometry of the inlayed thermocouple in a stratigraphic model of the firefighter glove whereas a layer has been used as static heat source. The relevant condition for the model is the calculation of the time dependent temperature on a certain point. Therefore a transient simulation of the heat transfer between a contact heat and the thermocouple contact has been used. Figure 2 shows a simplified schematic model of the stratigraphic geometry of the fire fighter glove.

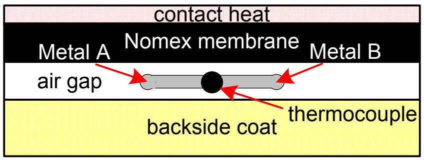


Figure 2. Schematic model of the glove geometry

It consists of a contact heat that is positioned directly onto a Nomex membrane [3]. The thermocouple is placed in between this membrane and a backside coat. The wire thickness is about 250 µm. Because in practice it is connected directly to an evaluation electronic, an air gap originates. The aim of this simplified model is to forecast the behavior of the heat transfer time constant. In real application, the heat transfer should offer a low reaction time to realize a fast measurement by contact. For this reason a parametric study of different air gaps, membrane and thermocouple wire thicknesses has been used.

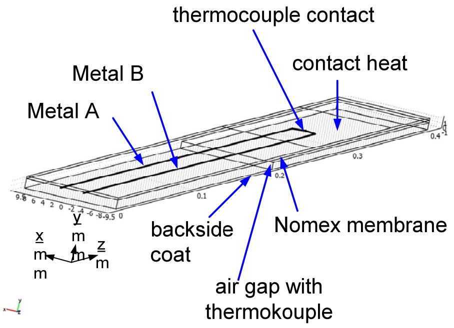


Figure 3. Simulation model of the glove geometry

The whole three dimensional simulation model is shown in fig. 3. As seen the contact heat is local around the thermocouple contact. The length of the thermocouple is about 30 cm.

3. Governing Equations

Since the thermocouple is a bimetallic sensor and regarding the Seeback (eq. 1), a voltage occurs concluding a heat difference between a reference point T_R and the measurement point T_M.

$$\Delta U = \int_{T_R}^{T_M} \alpha \cdot dT \qquad (1)$$

This difference can be measured between Metal A and B if a contact heat occurs. Using COMSOL Multiphysics the heat difference has been simulated with equation 2.

$$\rho C_p \frac{\delta T}{\delta t} = \nabla \cdot (k \nabla T) \qquad (2)$$

There, heat capacity C_p, heat conductivity k and the density ρ are only relevant. This heat difference has been transformed into a voltage using a polynomial approximation of the specific thermocouple TC (eq. 2).

$$\Delta U = \mathrm{v_u} \cdot \mathrm{c_{n,TC}} \cdot (\mathrm{T - T0})^{\mathrm{n}}, n \in \{0 \ldots 4\} \qquad (2)$$

In eq 2, v_u is an amplifier factor that also is used in the experiments. All coefficients for each thermocouple are described in [4]. Because the simulation aim was finding out a fast reaction time, all output voltages have been normalized with

$$U_{th} = \frac{U - U_{\min}}{U_{\max} - U_{\min}} \qquad (3)$$

to be compared among themselves and measurements.

4. Use of COMSOL Multiphysics

The whole glove geometry has been designed in COMSOL by using composite objects and blocks. Transforming equations have been defined as variables under global definitions. To aid a parametric interpretation, the heat transfer model doesn’t use the material browser. Instead, all necessary values like effective heat capacity, heat conductivity and specific density for all simulated thermocouples and glove materials are described as parameters. Initial values have been defined for each model layer and coupled to the Heat transfer in Fluids selection. There, heat conduction with parameter dependent thermal conductivity and thermodynamic properties like density and heat capacity are defined. The contact heat layer had a constant temperature of 373 Kelvin whereas 273 Kelvin was the ambient temperature.

5. Simulation results

The simulation model (fig. 3) has been used for a transient simulation of the heat transfer. First of all the most suitable thermocouple type has been simulated. This was done by simulation of the reaction time and normalizing the output voltage. The results can be seen in table 1.

Table 1. Simulation results of different thermocouple types [3].

	Umax / [mV]	Uth / [-]
type E	6,312	0,62
type N	2,603	0,61
type T	4,201	0,58
type K	3,992	0,65
type J	5,285	0,59

As seen, thermocouple type T offers the fastest reaction time of all. As next step the influence of air gap has been simulated (fig. 4).

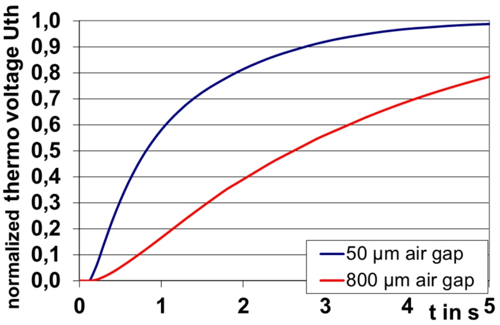
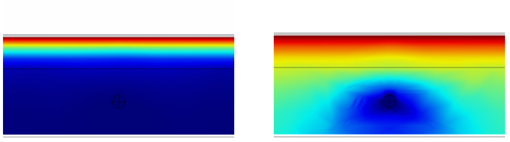
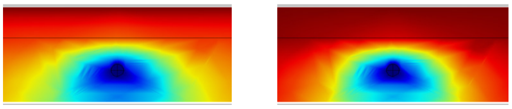


Figure 4. Simulation of the air gap, thermocouple type E.

As seen, a higher air gap causes a low reaction time. The result shows also a dead time between zero and 0,1 seconds. This is the time the heat need to go through the Nomex membrane. The lower the membrane thickness (and any else between thermocouple contact and contact heat), the shorter this dead time. Figure 5 shows a slide view of the simulation results without backside coat.



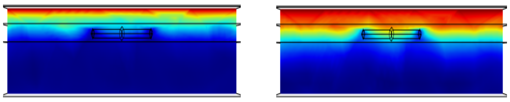
t = 0,1 sec, T_{min} = 0°C t = 0,5 sec, T_{min} = 5,6°



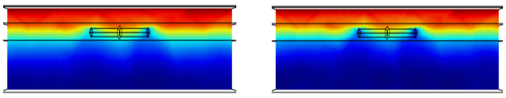
t = 1 sec, T_{min} = 17,6°C t = 5 sec, T_{min} = 77°C

Figure 5. Simulation of the heat transfer. through the glove geometry (without backside coat). T_{max} = 100 °C, type E, 250 µm wire diameter, 1mm Nomex thickness

The slide goes through the thermocouple contact that can be seen in the middle of the pictures. The reaction time in air is about a half second [5] and is not reached as can be seen in the upper right picture. The heat diffuses through the membrane and the air gap where the thermocouple is placed and reaches the contact delayed. This reaction time is maybe low enough for approximate heat detection, but in real application a backside coat has to be used for protection.



t = 0,1 sec, T_{min} = 0°C t = 0,5 sec, T_{min} = 3,5°C



t = 1 sec, T_{min} = 11,2°C t = 5 sec, T_{min} = 53,5°C

Figure 6. Simulation of the heat transfer through the glove geometry (with high density rockwool as backside coat). T_{max} = 100 °C, type T, 250 µm wire diameter, 0,5 mm Nomex thickness

This coat takes effect on thermocouple reaction time. Simulation results with high density rockwool as backside coat are shown in figure 6. The slide view shows a cut through both thermocouple metals. A comparison of different backside coat materials that are described in table 2 is shown in figure 7 whereas the simulation conditions are presented in table 2.

Table 2. Properties of simulated backside coat materials

backside coat		Air	Nomex	Rockwoll	
				low density	high density
heat conductivity	$\left[\frac{W}{m\cdot K}\right]$	0,025	0,2	0,039	0,046
density	$\left[\frac{kg}{m^3}\right]$	1,205	980	600	840
heat capacity	$\left[\frac{J}{kg\cdot K}\right]$	1006	180	10	100

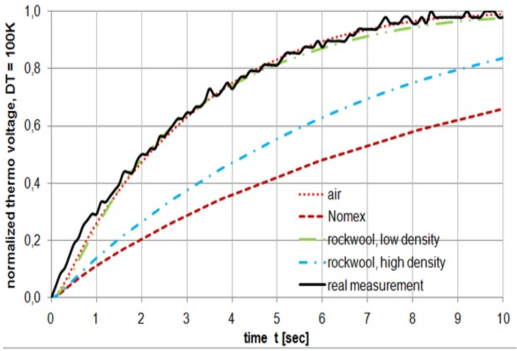


Figure 7. Normalized thermo voltage of the reaction time in a simulation of different backside coat materials, thermocouple type T

As can be seen in figure 7, rockwoll with low density has the fastest reaction time beside using air on backside. Any use of materials with higher density or the nomex itself improves the reaction time dramatically.
Thereby low density rockwool offered the best conditions for fast temperature measurements. This could be nearly reproduced with measurement results. There, low density felt with similar properties has been used instead of rockwool for practical measurements because rockwool is not common as glove layer. The measurements have been done by the glove electronics and protocolled via a serial port.

6. Conclusion

A schematic model for simulation of a textile integrated thermocouple has been created using COMSOL Multiphysics Heat transfer module. A polynomial explanation of the seebeck coefficient has been used to simulate the output voltage. The results show the behavior of the textile integrated thermocouple reaction time. Based on the simulations, a low density backside coat material has been chosen. The practical implementation of a fast heat detecting thermocouple showed the usability of previous simulation with COMSOL Multiphysics.

7. Acknowledgement

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