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Carbon Nanotube Fabric Cooling System for Firefighters and First Responders: Modeling and Simulation

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Abstract

This study investigates carbon nanotube textiles as advanced personal protection equipment for firefighters and first responders. Carbon nanotubes are lightweight, flame resistant, and possess high mechanical and thermal properties. Carbon nanotubes are also thermally anisotropic, meaning they easily conduct heat along the axis of an individual tube, and are relatively insulating across the tube's diameter. By recognizing this anisotropic behavior, heat transfer through a layer of aligned carbon nanotubes in a garment can be partially redirected to a cold reservoir thereby protecting the wearer from heat stress and exhaustion. Finite element models were developed to simulate a carbon nanotube layer embedded in a firefighting garment and thermally connected to a cold reservoir. Simulation showed that under heat stress conditions, firefighter skin temperature was considerably reduced by the cooling layer.

Keywords: Firefighter; Personal Protection; Carbon Nanotube Textile; Cooling

1 Introduction

Firefighting is a dangerous profession. Heat stress and heat exhaustion decrease performance and increase the risk for injury or death for firefighters and other first responders. In 2010, 87 firefighters died on duty in the US, and 63.2% of those fatalities were from heat-related complications [1]. The materials used to protect firefighters from heat were developed over 50 years ago (Kevlar/Nomex) and rely solely on passively insulating the wearer from the outside environment. If a firefighter garment could protect firefighters from the outside environment and also internal metabolic heat by directing heat out of the garment, it could reduce heat-stress-related fatalities.

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Carbon nanotubes (CNTs) have extraordinary mechanical [2-4] and thermal [5-7] properties, and are also lightweight [4], flame-resistant [8], and hydrophobic [8]. CNTs also have thermally anisotropic behavior [9]; a single CNT fiber is highly conductive along its axis and relativity insulating across its diameter. These properties may enable the next generation of firefighter Personal Protective Equipment (PPE) to be developed. By creating a bulk textile material where the fibers are aligned in the plane of the material (creating a material that is conductive along one axis in-plane and insulating in the other orientations), a hypothesis can be formed: CNT textiles thermally connected to a cold reservoir or sink could improve occupational safety for firefighters and other first responders [10]. This would be achieved by redirecting the heat flux away from the wearer therefore reducing the heat stress on the wearer. Heat enters the firefighters garment due to exposure to the environment and also from heat generated by the body. In this new approach called a smart garment, heat is transferred from the garment to an external cold reservoir or sink (i.e. to a lower temperature material than the wearer and the ambient environment). The design of the smart cooled garment is illustrated in Fig. 1.

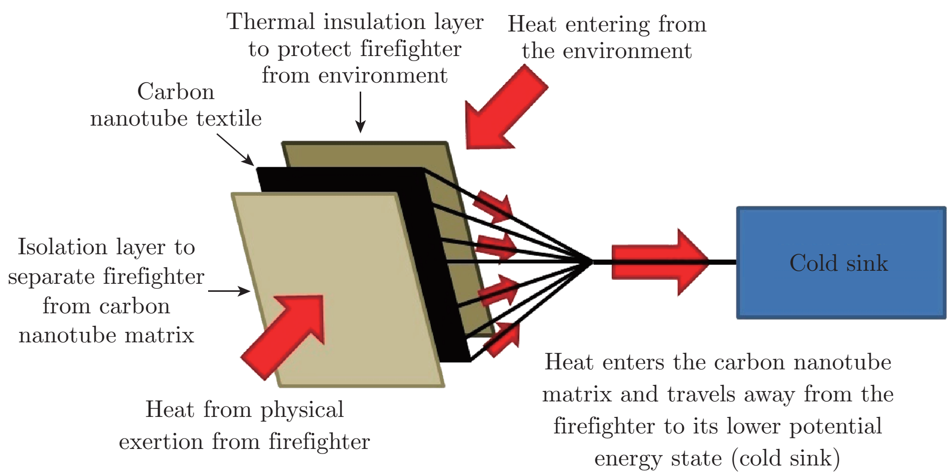

Fig. 1: Schematic of smart cooling for protecting firefighters from heat stress. The smart system draws heat out of the garment to a cold reservoir or sink rather than just relying on passive heat insulation from the environment to keep the firefighter cool

2 Methodology

Finite Element Analysis (FEA) models were constructed to test the effectiveness of CNT fabric integrated into firefighting garments supplemented with a cold reservoir to protect the wearer from heat stress. Modeling is a cost-effective way to rapidly evaluate the performance of nanotube material without having to manufacture test garments of different designs. This simulation based approach was chosen to give a first indication how successfully heat can be piped out of a firefighter garment. The FEA models were also generated because the parameters of the system can easily be changed to obtain a deeper understanding of the components' interactions with each other and to aid in future design. The model developed herein provides guidelines on performance of the proposed design, but is an approximate model. A more elaborate model for the firefighter and garment system would add too much complexity (environment, garment, cold reservoir, and body) at this time. Thus experimental testing of fabric swatches is the next step. Looking ahead,