Cooling System Embedded Turnout Coat Liner Prototype Development of Personal Protective Equipment

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Background: Firefighters (FFs) experience significant hazards on the job common fireground injuries include overexertion and slips/trips, and falls, as well as exposure-related injury. Heat Stress, or hyperthermia, is dangerous, and has both short- and long-term health consequences. FFs pointed out an automated body cooling system as a top priority and a monitoring system for heart rate, location, blood pressure, body temperature, noxious gas is also priority (Kim et al., 2022). This evidence indicates that improvements to these features are urgently necessary to satisfy FF needs and wants for better physical protection and satisfaction. Therefore, this study aims to 1) create a turnout gear coat liner prototype that has an on-demand cooling system, 2) evaluate the performance of the cooling garment system with Infrared Camera, and 3) evaluate the performance of the prototype with sweat thermal mannequin test.

Literature Review: Active cooling can reduce both the cardiovascular and thermoregulatory strain, while significantly increasing tolerance time and total working time where operationally necessary (Selkirk et al., 2004). Even though a separate vest cooling under full PPE improved exercise time and attenuated physical strain during exercise (Kenny et al., 2011; Kim et al., 2020), the vest is an additional garment on top of the existing one. There is a need to investigate on creating a cooling system embedded in the existing garment with an option for the FFs to remove the cooling system as needed.

Method: The study formed a prototype development team with 11 researchers from Fashion design, Engineering, and an industrial partner (Lion Protects Inc.). The mock-up fabrication was made for a preliminary evaluation. The final fabric was made by integrating the Carbon Nanotube (CNT) sheet into the existing liner layup materials. The study preliminarily evaluated the performance of the mock-up prototype with an Infrared (IR) camera record and CO2 sensor. For the final prototype test, the study evaluated a core body temperature change over 45 minutes using a sweat thermal mannequin at National Institute for Occupational Safety & Health (NIOSH).

Results/Findings: 1) Turnout Coat Prototype Development: A preliminary prototype design was developed in collaboration with an industry partner (Lion) and a local Fire Department. Lion provided the team with a current turnout coat design, technical packages, its shell and liner patterns, along with fabrics to produce the fabric samples and mock-up sample. The team gained critical feedback from industry on production limitations and possibilities, challenges of scaling up. The local Fire Department lent the team self-contained breathing apparatus (SCBA) for the research and gave feedback and comments. The first coat liner mock-up sample was created using a mock-up muslin layup that mimics current market coat liner in thickness and weight. After

preliminary test, the first prototype was created using the CNT sheet material fabrication. The material fabrication was provided by collaborator of engineering researchers, by adding the CNT sheet into the existing coat liner to produce a novel fabric (Schulz et al., 2020).

The body size of the first prototype was customized for a sweat mannequin at NIOSH. The team oversaw the creation of the first prototype (produced by Lion) of an active cooling garment system, which has a removable option from the coat using a core guard, along with providing on-demand active cooling with a turn-on/off switch. The core guard is a feature of the existing turnout coat design to block the harmful ambient air. It functions in our design as an additional detachable panel that functions to hold all cooling components and to provide filtered clean air to the firefighters' body skin. The study used the active cooling apparatus that was created by Engineering team (Cooley et al., 2023) and it has a battery/switch, blower fans, passive cooling ice packs, a vented pouch to hold the cold ice packs, a customized fire-resistant HEPA filter to remove harmful gas and airborne particulate, and housing to hold all components together and direct flow efficiently into the inside of the garment. The active cooling apparatus delivers cooled air through the duct of the housing. The housing was customized utilizing a 3D printer. The prototype is a CNT Active Textile integrated removable turnout coat liner that interfaces with existing Lion Express model firefighter turnout coats.

2) Preliminary Evaluation of Cooling System with Infrared Camera and CO2 Sensor: The study evaluated the effectiveness of the coat liner cooling system using an IR camera and a CO2 sensor with variations of blower fans and forced cooling materials with the shell layer and without the shell layer. Based on the test results, the study confirmed the optimal cooling approach to go forward with. IR camera showed a positive cooling and spreading effect with a forced cooling and blower fans. The study tested two different methods of dry ice and cold ice packs. The dry ice resulted in the best cooling performance. However, it also released over 5000ppm Co2 measured by Co2 sensor. Since the upper limit of the CO2 is 5000 ppm as regulated by the Occupational Safety and Health Administration (OSHA) safety, the study confirmed to use the ice packs as they provide cooled air in a safe manner. The study also evaluated the performance of two types of blower fans and found that fire-resistant metal one's performance is better, so the study also determined the blower fan. This evaluation provided reasonable preliminary data to determine which of the fan and forced cooling methods for the final design for optimal cooling. With these results, the study confirmed the first prototype coat liner design options. The first prototype coat liner has been constructed by Lion sample makers in their production facilities using their equipment and trained sewing technicians producing the garment to specifications.

3) Cooling Garment System Evaluation with Sweat Thermal Mannequin: An ensemble, consists of the first prototype coat and a commercial turnout pants, was tested on a sweat thermal mannequin in a controlled chamber at NIOSH with ambient 22°C and heated 35°C in 20% of Relative Humidity condition. The study measured the core body temperature (CBT) at starting point and run for 45 minutes and measured the finishing point and calculated the CBT change over 45-minute interval in both 22°C and 35°C. The test sets of ensembles were 1) coat with standard liner that is commercially available, which is a control group, 2) coat with CNT embedded liner

but the cooling system is off, 3) Coat with CNT liner and cooling fans is on but without cold ice packs, and 4) coat with CNT liner and fans on and cold ice packs in. The results clearly shows that the effectiveness of integrated CNT embedded cooling system. At 22°C, the CBT of coat with fans on/ice in only increased 2.212°C while that of standard liner without cooling system increased by 3.672°C. At 35°C heated condition, the CBT of coat with Fans on/no ice only increased 3.137°C while the coat with standard liner increased 4.379°C.

Conclusion and Limitations: The study confirmed that performance of active cooling system works better than the standard liner at ambient temperature and heated condition. It is obvious that the performance of CNT integrated AT cooling system with or without cold ice packs in works effectively in both temperature of 22°C and 35°C, especially the results of at 35°C is meaningful comparing that of coat with standard liner that does not have the cooling system. This is because the 1°C of the CBT results can reduce significant heat related illness. However, due to a small sample size of case study in testing and sweat mannequin test, not human test, the data is limited in its application and interpretation/implications. Thus, the study suggests expanding this study to substantial number of human tests so that the study can confirm that the effectiveness of the cooling system that will increase firefighter safety, protection, and comfort, from heat stress, burn injuries, and other potential health issues.

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