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Influence of Wet Cooling Vest on Firefighters' Protective Clothing ⋆

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Abstract

Firefighters' Protective Clothing (FPC) is essential for protection against thermal and physical threats. FPC must be comfortable, enable heat transfer from the wearer to the environment and should not restrict motion of body parts. The application of a cooling vest under protective clothing may prevent overheating by cooling at the microenvironment level while working in a hot environment during firefighting. In this study, the effect of using a passive system, in the form of a nonwoven fleece material, was investigated. This system was distributed across the surface of a vest on the upper front chest and back. In this passive system, hydro-crystals swell on contact with cold water, lowering body temperature or holding the body temperature at a normal level. The thermal insulation of the wet and dry cooling vest was tested using a thermal manikin. Results showed that the thermal resistance of the system dropped significantly due to replacement of dry air with moist air with higher thermal conductivity. This reduction was proportional to the amount of moisture present within the system.

Keywords: Cooling Vest; Firefighters' Protective Clothing; Thermal Manikin; Hydro-crystals

1 Introduction

Firefighters' Protective Clothing (FPC) must comply with the standards such as BS EN 469 and AS 4967-2009 to assure their protective properties against life threating risks and skin burns. FPC is usually a multilayer construction (three or four layers) of different fabrics to provide essential protection [1-3]. However, this multi-layered fabric system makes heat exchange between the human body and the environment difficult, due to the presence of a semi-permeable or impermeable moisture barrier. The restriction of metabolic heat exchange with the environment may lead to heat stress for the firefighters. As a consequence, it may result in accumulation of sweat

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under the clothing next to the skin. This in turn may lead to a reduction in comfort, reducing performance and even becoming life threatening in an extreme hot environment [1, 2].

Several researchers, Havenith and Heus [4], Groeller and Taylor [5], Raimundo and Figueiredo [6], have studied the influence of FPC on fire safety improvement and optimization, heat production and injury prevention. These studies focus on the environmental working conditions to which firefighters are exposed, on simulations of thermoregulatory responses and on parameters of firefighter's clothing. FPC properties have to be investigated in details as accumulation of heat in the human body and sweat in the microenvironment of clothing mostly depend on the garment characteristics. Generally, metabolic heat and generated sweat are captured between the human skin and the outer shell of FPC, due to the structure of this type of protective clothing which includes an impermeable or semi-permeable layer to prevent chemical slippage into the system. Such a layer reduces the breathability of the FPC, while restricting heat and moisture transfer from inside the system to the environment. It is clear that this impacts on the physiological and behavioral reactions of firefighters' and may cause significant undesired reactions, namely introversion (violent sweating, loss of judgment, amnesia), superficial skin damage (pain and first degree burns), heat stroke (fainting, cessation of sweating, central nervous system alteration) and permanent injuries (greater than first degree burn, brain damage or, in more serious cases, death) [4-6]. A variety of systems are used for cooling firefighters during work out as shown in Fig. 1.

(a) (b) (c) (d) (e)

Fig. 1: Systems for cooling firefighters: (a) Drager, (b) Arctic Heat, (c) Cool Comfort, (d) Flexi Ice Vest [7, 8, 9, 10] and (e) Cooling vest [11]

Each system differs in performance over time and functionality. The focus of this paper is on the passive cooling system using a cooling vest. The passive system, in the form of a nonwoven fleece material, was distributed across the surface of a vest on the upper chest and back. A nonwoven fleece with hydro-crystals swells on contact with cold water and, in turn, cools the wearer or keeps their skin temperature at normal levels. The lower part of the vest was made of a polyester air-netted material. We hypothesize that this cooling vest can decrease the thermal insulation of firefighters' clothing. The cooling vest may be used while performing high intensity work, such as firefighting, and can be used as standalone product or in combination with other breathable or non-breathable clothing [11]. Furthermore, it may be used as a pre-cooling system prior to activity, as inter-cooling during activity and as post- cooling after high intensity work.

In this study, the effect of presence of a cooling vest on the thermo-physiological comfort of firefighters was investigated. It was hypothesized that the cooling vest would help to maintain a low skin temperature, due to the water evaporation from the cooling vest and higher thermal conductivity of the moist air in comparison with the dry air [11]. Experiments were performed using a thermal manikin with a dry and wet cooling vest worn under the FPC and covered with an impermeable PVC membrane to prevent heat loss by evaporation and mass transfer.

2 Experimental

2.1 Materials

The firefighters' protective jacket used in this study consisted of three layers, manufactured by Australian Defense Apparel (ADA), Melbourne. The cooling vest used was a knitted singlet made of 100% cotton, manufactured by Prevent & Deloza Ltd. Jacket and cooling vest specifications are shown in Table 1.

Table 1: Material specifications used in firefighters' jacket and cooling vest

Clothing items		Composition	Materials
Firefighter's jacket	Inner liner (next to skin)	100% Nomex	Rip-stop fabric with thickness = 0.27 mm and areal density = 129 g/m^2
	Thermal barrier	Polytetrafluroethylene (PTFE)	Semi permeable coated fabric with thickness = 2.29 mm, area density=313 g/m^2
	Outer layer	60% Kevlar/40% Polybenzimidazole (PBI)	Rip stop fabric with thickness = 0.47 mm and area density=218 g/m^2
Cooling vest (singlet)		100% Cotton	Hydrophobic crystals that swells in contact with the water [11]

2.2 Methods

2.2.1 Thermal Manikin

Thermal resistance and thermal insulation of the firefighters' protective jacket with and without the cooling vest were evaluated using the Newton P357 thermal manikin from Measurement Technology, Northwest (USA). The manikin consisted of 20 independently controlled thermal zones. Details of the tested ensembles are given in Table 2. The experiments were carried out in dry testing conditions with both the dry and wet cooling vest (wet-dry or dry-dry, ensemble).

Table 2: Detailed of ensembles tested by thermal manikin

Sample code	Description	Final layer
A	Cooling vest only	Ensembles were covered by impermeable PVC membrane
B	Cooling vest covered with jacket	

The tests were performed with the cooling vest only and the cooling vest covered with the firefighter's jacket, both tested ensembles were covered with the impermeable PVC membrane. In the first set of experiments the cooling vest was tested wet and dry and in the second set for both wet and dry conditions was covered with the firefighter's jacket. The ensembles were then covered by an impermeable PVC to prevent water vapour escaping from the system. Changes in the thermal insulation were measured as a result of changes in conductivity, not evaporation of the system. The test assemblies are shown in Fig. 2.

(a) (b)

Fig. 2: Thermal manikin clothed with: (a) cooling vest and PVC membrane (A), and (b) firefighter's ensemble and PVC membrane (B)

The cooling vest A (Table 2) was pre-wetted prior to testing, by immersing into warm distilled water for 2 minutes and then placed on a towel and rinsed. An external impermeable PVC membrane was used to cover the manikin, sealed with adhesive tape at the wrist, neck and at the top of the thigh.

In the second set of experiments the thermal resistance of ensemble B was measured by covering the manikin with the wet/dry cooling vest A, dry jacket and an external impermeable PVC membrane. This cover was air tightened and sealed to prevent moisture and liquid escaping from the system into the environment. All tests were performed in the Climatic Chamber under the controlled environmental conditions, 23 ± 1°C and relative humidity (RH) of 50% ± 3%, in accordance with ASTM F1291 (Standard test method for measuring the thermal insulation of clothing using a heated manikin). The humidity of the room did not have a significant effect on the test conditions as the test was run in the closed environment (closed by the PVC membrane). The clothing factor was considered constant at 1.48 for the jacket; the measurements were performed with the standing and walking manikin. Four walking speeds; 0, 1.6, 2.4 and 3.2 km/h, were considered for this test to investigate the effect of physical activity and motion on the thermal resistance of the ensemble.

In all experiments "parallel-thermal resistance" was measured, using uniform skin temperature which is closer to the real situation during firefighting. The manikin skin temperature was set to 35°C and all manikin results were calculated for the area covered by the cooling vest/Jacket (A=0.8838 m^2). After the system reached a steady state, total thermal resistance of the ensemble was governed by equation 1 (ASTM F1291) [12]:

$$R_{ct} = [(A(T_m - T_a))/(H - \Delta H_c)] - R_{ct0} \quad (m^2 \cdot ^\circ C/W) \tag{1}$$

where, R_{ct} is the thermal resistance of the ensemble ($m^2 \cdot$°C/W), A is the area covered by the ensemble (m^2); T_m and T_a are the measuring skin temperature and ambient air temperatures of the chamber (°C), respectively; H is the electrical power supplied to the manikin to maintain the measuring skin temperature at 35 ± 0.1 °C (W); ΔH_c is the correction factor for dry testing (W) and R_{ct0} is the nude thermal resistance reading without any ensemble ($m^2 \cdot$°C/W). The total heat loss (THL) was measured by equation 2:

$$THL = H_a/A \tag{2}$$

where, H_a is the generated heat (W), and A is the total covered area=0.883 8 m^2.

Estimated cooling rate (ECR) was measured by equation 3:

$$\mathrm{ECR} = \mathrm{Qi(new)} - \mathrm{Qi(old)} \tag{3}$$

where Qi (new) is zone power output of new test (W) and Qi (old) is zone power output of baseline (W).

2.3 Statistical Analysis

The difference between the average results obtained in manikin tests was estimated using the single factor analysis of variance (ANOVA) using Excel 2013 at $p \leq 0.05$ levels.

3 Results and Discussion

The thermal manikin study was performed in order to investigate the effect of the cooling vest on the thermal insulation, cooling rate and heat loss of protective clothing in simulated firefighting conditions. The manikin test results for thermal resistance and total heat loss of ensemble *B* in "dry vest-dry jacket" (DV-DJ) and "wet vest-dry jacket" (WV-DJ) are presented in Fig. 3. In the current study, all tests of the cooling vest and ensemble B, were covered by the impermeable PVC membrane to prevent evaporation to the surrounding environment. As a result, some of the evaporated water from cooling vest was trapped between the outer layer and PVC film and releasing heat to the environment. The released heat to the environment caused by the convection as the temperature of the environment was lower.

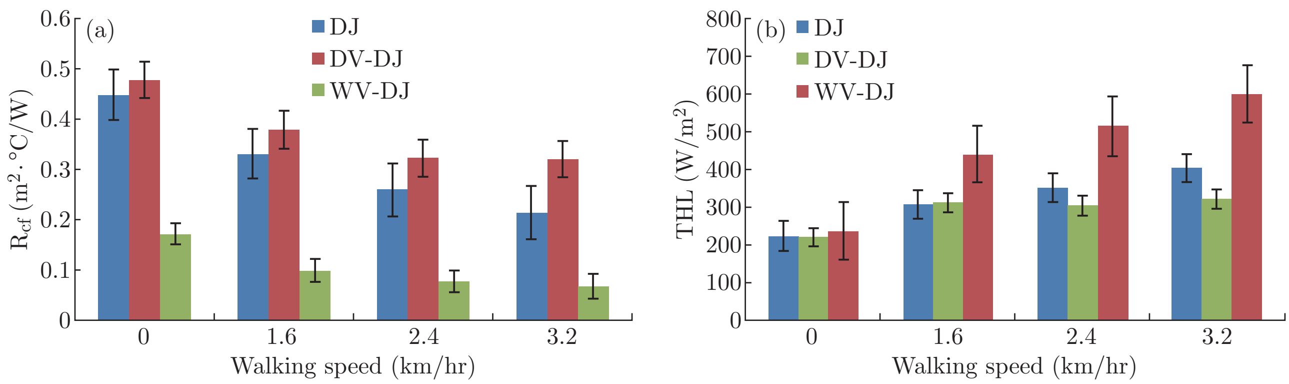

Fig. 3: Thermal resistance (R_{cf}) and total heat loss (THL) of Dry jacket (DJ), wet vest and dry jacket (WV-DJ) and dry vest and dry jacket (DV-DJ) for various walking speeds

It can be observed from Fig. 3 that by wetting the cooling vest, the thermal insulation of ensemble *B* dropped significantly. When compared to tests without the cooling vest, there is a 61%, 70%, 70% and 69% drop in the thermal insulation of ensemble *B*, with the wet cooling vest at walking speeds of 0, 1.6, 2.4 and 3.2 km/h, respectively. The same trend was observed for heat loss, with the addition of a wet cooling vest to the system resulting in an increment increase in total heat loss. This phenomenon may be due to the result of the hydro-crystals inside the cooling vest swelling in their wet state. The evaporation of water trapped in the hydro-crystals cooled the wearer and helped to maintain skin temperature at normal levels.

Water present inside the cooling vest evaporated with the absorption of energy from the skin of the manikin, and led in lowering down the skin temperature. Therefore manikin produced more heat to keep the skin temperature at 35°C in the wet condition.

In ensemble *B*, wet-dry conditions more energy would be absorbed by the trapped water inside the cooling vest to be evaporated in comparison with the dry-dry condition, which resulted in lowering down the skin temperature and keep the wearer cooler by absorbing more released metabolic heat from body.

On the other hand, in wet-dry (WV-DJ) ensemble *B*, the air layer inside the system would be gradually replaced by the evaporated moisture which facilitated the heat transfer from the cooling vest to the environment due to the higher thermal conductivity of moist air in comparison with dry air.

It means in the wet cooling vest and dry jacket system, produced heat flux by the body would be consumed by trapped water inside the cooling vest, resulting in water evaporation. The evaporated water would be transferred and condensed inside the outer layer of the jacket or the PVC membrane. When most of the water has been evaporated and the air inside the system has been saturated by the evaporated water, heat flux slowly increased and the measured parameters would be closer to the dry-dry condition. This means that heat stress may be reduced for a short period of time but with no significant long lasting effect.

There was a significant difference between the THL of the system in a stand steady position and in the dynamic mode (walking). However, variation in walking speed did not result in significant change in THL of dry system. In the dynamic mode, circulation and the movement of air and moisture inside the closed system has a significant effect on heat loss in the system. In this mode, dry and moist air circulates aiding in the transference of heat into the environment. However, with the addition of the PVC membrane, air flow and moisture exchange to the environment was limited.

The effect of the wet cooling vest on estimated cooling rates in the stand steady and dynamic positions (walking and physical activity) is given in Fig. 4.

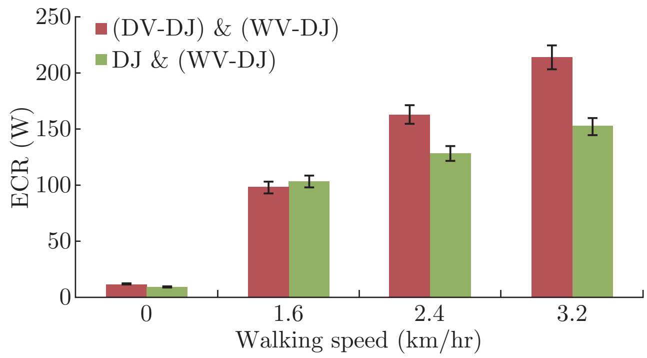

Fig. 4: Estimated cooling rates for wet vest-dry jacket (WV-DJ) and dry vest-dry jacket (DV-DJ) for various walking speeds (km/h)

It can be seen in Fig. 4, there is a substantial increase in the cooling rate of the ensemble with the addition of the wet cooling vest when compared with the dry jacket. There was a 5%, 43%, 47% and 48% increase for the system with the wet cooling vest for walking speeds of 0, 1.6, 2.4 and 3.2 km/hr, respectively. It may be concluded that the addition of the wet cooling vest to the system resulted in a heat reduction inside the system, with a subsequent increase in the cooling rate. However, variation in walking speed resulted in significant change, the PVC cover causes restriction in heat and moisture transfer from inside the system to the environment.

The amount of the water content inside the system also has an effect on the thermal insulation of the ensembles. In a separate experiment the effect of the amount of the water trapped in a cooling vest has been investigated with results shown in Table 3.

Table 3: Thermal resistance of the cooling vest ensembles B with various amounts of water content

Conditions	R_{cf} ($m^2 \cdot °C/W$)	
	Average	Standard deviation
Dry cooling vest covered with PVC	0.14	0.01
Semi-wetted (50%) cooling vest covered with PVC	0.08	0.01
Wetted cooling vest covered with PVC	0.05	0.02
Dry cooling vest covered with jacket and PVC	0.38	0.02
Semi-wetted (50%) cooling vest covered with jacket and PVC	0.26	0.01
Wetted cooling vest covered with jacket and PVC	0.13	0.01

As may be seen in Table 3, reduction in the thermal insulation of the wet vest was increased significantly from 42% to 65%, when the moisture content of the system was increased from 50% (semi-wet) to 100% (fully- wet), respectively. Wetting the cooling vest in the ensemble resulted in a reduction in the thermal insulation of the system by 32% and 65%, when the moisture content of the system was 50% (semi-wet) and 100% (fully-wet), respectively. This can be explained by the fact that evaporation occurred close to the skin, resulting in a reduction in skin temperature. These results confirmed that the high thermal resistance of the dry jacket dropped with the placement of the cooling vest under the garment. Even with an additional covering of PVC membrane, the thermal resistance of the ensemble was lower than that of the dry jacket alone.

The cooling vest was covered by the impermeable PVC membrane to prevent evaporation to the surrounding environment. As a result, some moisture evaporated from the cooling vest, which, due to the latent heat of the evaporative cooling, condensed inside the PVC membrane. This led to a release of heat and a raise in the temperature of the film. Dry heat loss to the environment from the system increased due to the rise in the temperature of the film. This resulted in more moisture condensation inside the membrane that had been transferred from the cooling vest to this layer.

Wicking was an important factor in transferring moisture from the cooling vest to the PVC membrane. However, wicking was stopped before reaching the semi permeable layer, (thermal barrier), inside the jacket, which allowed the passage of the moisture to the outer layer only and led to moisture accumulation and an elevation in the temperature of the fabric membrane. This mechanism helped in greater moisture evaporation and heat loss to the environment from inside the system and elevated the rate of condensation inside the PVC membrane.

Several studies by Havenith et al. [13], Wang et al. [14] and Brode et al. [15] confirmed this mechanism. It means that by pre-wetting the garment close to the skin, the chances of heat strain can be reduced due to the higher thermal conductively of the wet garment and the location of the wet layer in the system.

The produced cooling vest with hydro-crystals provided the conditions which resulted in a reduction in heat strain and improved comfort of the wearer. However, further investigation is required to consider steam burn during activity at high temperature. This system should be investigated for wildland firefighters, as there is no impermeable layer in this system. The moisture may therefore evaporate and be released into the environment, helping to cool firefighters while absorbing sweat during the workout.

4 Conclusion

This study investigated the effect of a wet cooling vest on the thermal insulation of the firefighters' ensemble. Experiments were performed on the manikin at various walking speeds to consider the effect of physical activity and metabolic heat rate. Cooling rates and changes in produced heat flux were recorded. An increase in heat flux was found with an increase in the walking speed that led in lowering down the thermal insulation of the system. The introduction of a cooling vest into the system has also resulted in significant drop in the thermal insulation of the system while cooling rate was improved.

In real-life conditions, a reduction in heat flux would result in a cooling of skin temperature, whereas the manikin's skin temperature was maintained at a constant level. Generally, introducing water inside the ensemble reduces the thermal insulation and heat stress while increasing the cooling rate. However, the covering layer is an important consideration as the structure of the protective clothing for a firefighter includes an impermeable layer which may reduce these effects and possibly result in steam burning. Further study is required to investigate the mechanism of the moisture transfer from the under layer to the environment.

A possible avenue of investigation might be to combine the protocols of intermittent working periods; pre-, inter- and post cooling, while investigating the feasibility of developing and producing thinner and lighter clothing for harsh environments. Additional investigation is recommended to combine this system with wildland firefighters' protective clothing as no impermeable layer is included. Moisture inside the cooling vest may therefore evaporate to release and transfer heat from the wearer into the environment. Sweat would be absorbed by the dried cooling, leading to less damp skin and activating the hydro-crystals.

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