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Thermal protective properties of a firefighter turnout gear with and without an accessory on top of turnout jacket

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ABSTRACT

Thermal insulation and evaporative resistance of protective clothing are basic parameters that influence thermal stress and human performance. During training, the firefighter instructors wear an accessory (bolero) to discriminate them from the exercising personnel. Such boleros may be available at training sites in one size only. At one training site an instructor repeatedly reported pain sensation and first degree burns, while at another site problems did not occur, while similar amount of fuel in fires and comparable weather conditions were expected to lead to the same heat and radiation load. The other suspected reasons for pain and burns could be the aging effect on clothing properties, different materials in turnout gear compared to the materials in original procurement or the effect of the size of the added bolero. This limited study measured the thermal properties of the protective ensemble used by the firefighters today and focused on the case of the influence of clothing and bolero size on thermal insulation by the means of a thermal manikin. The tests complemented test series on firefighter ensembles commonly used in different incident scenarios. Additionally, a correct size and one size bigger ensemble were tested both with and without bolero. Use of bolero showed 3.6-6.7% insulation increase for size L, and no change or slight reduction for XL, indicating increasing thermal risks during exposure to heat and flames when protective layers get compressed by using wrong sizes.

Keywords
firefighter,
protective clothing,
sizing,
bolero,
insulation,
burn injury risk

1 Introduction

Based on manikin (and material) measurements, a firefighter clothing database was created [1] to support proper thermo-physiological model selection for predicting thermal load on firefighters. For validation specially designed human studies were carried out [2]. During the human study preparations there came up a request to include also other, commonly used firefighter turnout gear configurations to the experiments. As these configurations had not been measured on manikin before, then it was decided to carry out complementary tests in order to acquire overall and regional clothing thermal insulation and evaporative resistance values that would meet the validation needs of both robust and highly complex models [3] in order to predict thermal stress development during firefighter work in various incident scenarios. Such models should act as basis for specialized decision aids and for activity planning [4,5].

At the same time, there were reported pain and (first degree) burn cases during training. The extra tests were included in the planned complementary manikin measurement series in order to explain the adverse event. These dedicated tests would also allow investigating usability of detailed regional clothing properties. The adverse event was suspected to be related to the use of an accessory, the so-called bolero that covers shoulders and arms and is worn during training by the instructors in order to discriminate them from the exercising personnel. In some cases these boleros are available at training sites in one size only.

The adverse events were reported by an instructor working at different training sites and specified that at one training location he is prone to pain sensation and suffer burns. The affected person was interviewed for incident reporting about the tasks over day and about what happened. Although influence of environmental conditions cannot be ruled then it was also mentioned that the radiation from the created fires was expected to be the same at different sites as the amount of fuel and the weather conditions were comparable. Other suspected reasons for pain and burns were the possibility of clothing properties change with time (aging), different materials used in the protective clothing compared to original procurement or the effect of the size of the added bolero. However, original and new material packages were not available for comparative testing. Therefore, size and fit effects were evaluated on thermal manikin.

From earlier studies it is known that a size larger clothing items may lead to about 4% higher insulation, while the use of smaller size may lead to up to 10% insulation loss [6,7]. There is a clear relationship between fit, i.e. air gap, in clothing and insulation [8-11]. In addition to collecting the detailed basic thermal properties of firefighter protective ensembles for various incident scenarios, this study also aimed to investigate the influence of clothing and bolero size on local thermal insulation by the measurements on a standing thermal manikin. The assumption was that an added layer of correct size bolero (L) would improve local insulation of size L clothing, while the same bolero size on size XL clothing would create compression and reduce insulation instead.

2 Methods

2.1 The thermal manikin

The thermal manikin Tore [12] at Lund University was used for testing in the climatic chambers of the Department of Design Sciences, Division of Ergonomics and Aerosol Technology. The manikin has a total surface area of 1.774 m^2 that is divided into 17 individually controlled zones. For the purpose of these measurements with bolero the upper arm circumference of the manikin and the affected firefighter were measured. The circumference of the manikin upper arm in its middle is 31.5 cm. This is between the circumferences measured on a person when having the upper arm in relaxed (29 cm) or muscles tensed (34 cm) position. The manikin surface temperature in all zones was kept constant at 34 °C for both insulation and evaporative resistance measurements.

2.2 Testing procedures

The same procedures and calculation principles as described in the earlier paper [1] were followed also this time. Manikin surface temperatures and heat losses were recorded at ten-second intervals. The last

10 minutes of stable state were used for thermal insulation calculation or evaporative resistance calculations, respectively. Based on series of the measurements and requirements in EN 342 [13], the differences exceeding 4% were considered significant.

2.2.1 Thermal insulation

The tests for total thermal insulation (I_T) were carried out on the manikin in a standing position according to ISO 15831 [14] following ISO 9920 [15] recommendations for low air velocity. Air layer insulation (I_a) was measured with a nude manikin. The basic insulation of each clothing ensemble (I_{cl}) was calculated. For testing insulation, the chamber temperature was set to 10 °C and the air velocity stayed around (0.22 ± 0.09) m/s. Insulation calculations were carried out according to the global method [16].

2.2.2 Evaporative resistance

The total evaporative resistance ($R_{et,raw}$) of selected clothing ensembles was measured according to ASTM F2370-16 [17] on the manikin in standing position under so-called isothermal conditions that were set to 34 °C. The corrected evaporative resistance values (R_{et}) were calculated according to Wang et al. [18]. Finally, clothing evaporative resistance (R_{ecl}) and permeability indices (i_m and $i_{m,cl}$) of the ensembles were calculated.

2.2.3 Test environments

Ambient air temperature was continuously monitored using three sensors (PT 100, Pico Technology Ltd., St. Neots, UK) positioned adjacent to the ankles, the mid-trunk, and the head (vertical heights of 0.1, 1.1, and 1.7 m from the soles of the manikin). Relative humidity was measured with the Humidity Sensor Evaluation Kit EK-H3 with pin SHT75 sensors (Sensirion AG, Stäfa, Switzerland) positioned at the same sites as the air temperature sensors. The mean radiant temperature was equal to the air temperature. Similar to manikin surface temperatures and heat losses, also the environment temperatures and relative humidity were recorded at ten-second intervals.

Any differences in measurement conditions, compared to earlier tests [1], might have been caused by that the present tests were carried out in a new climate chamber where air flow patterns did differ compared to the old chamber. For example, during evaporative resistance measurements air velocity on average stayed at (0.33 ± 0.12) m/s (based on measurements in 15 points in front of the manikin) instead of 0.4 m/s as was in the earlier study. For both insulation measurements at operative temperature of 10 °C and evaporative resistance measurements at 34 °C, the chamber was stable with temperature variation within ± 0.1 °C. During the stable state of each evaporative resistance measurement, the variation in the relative humidity was less than ± 2%.

2.2.4 Measurements of clothing area factor (f_{cl})

Photographic method based on 2 photos was used to estimate clothing area factor (f_{cl}) of the individual garments and the ensembles [19,20]. The frontal and the side photos were used.

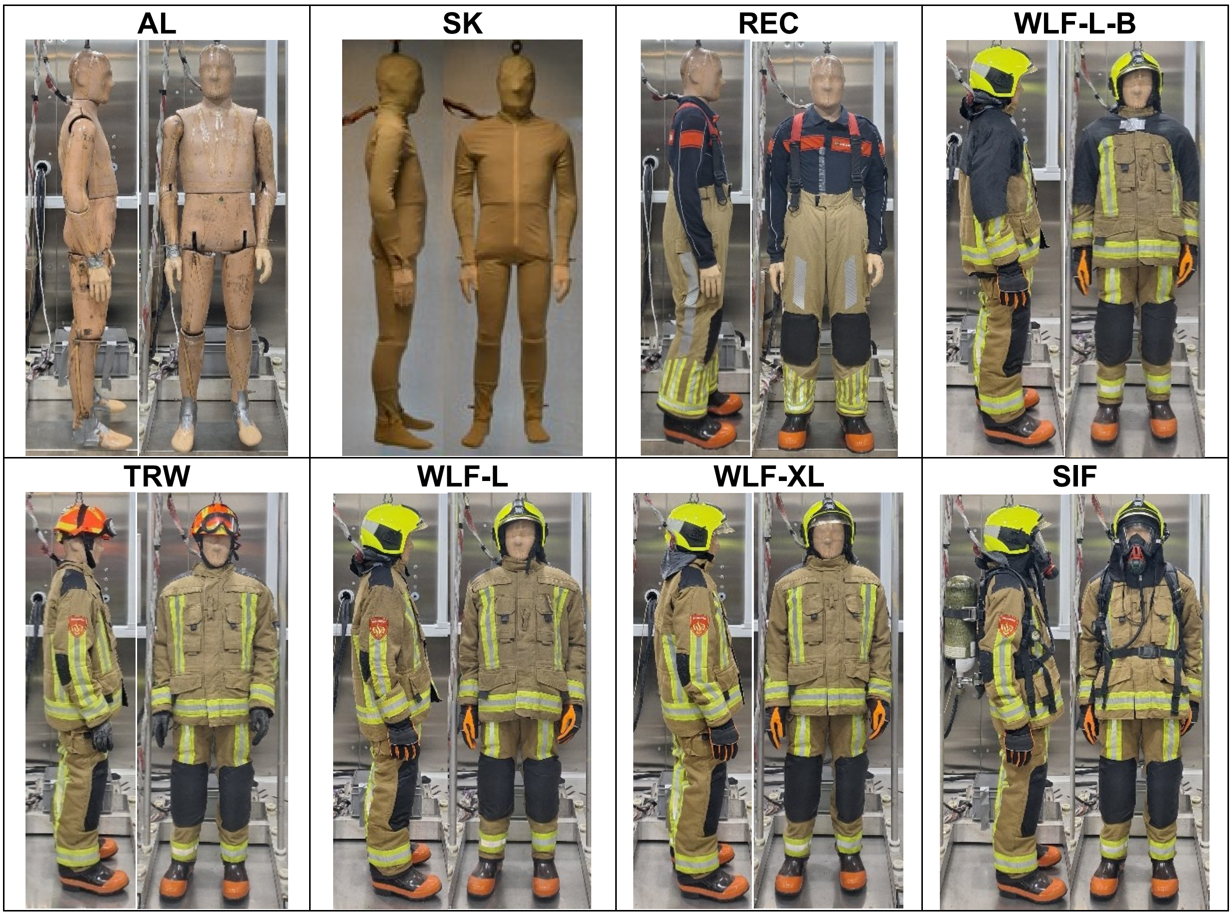
2.3 Clothing

The firefighter personal protective clothing (PPC) sets are shown in Table 1. They represented the combinations commonly used in various incident scenarios: technical rescue (TRW), wildland firefighting (WLF) and internal structural firefighting (SIF). In addition, a typical clothing combination without gloves jacket and head protection that is often used during recovery periods (REC) was also measured. This condition was measured also with another pair of firefighter turnout trousers from a different manufacturer (REC vs. other sets in Table 1). However, as the result with the other trousers was 1.4%, then all other combinations were tested only with the trousers matching the jackets.

All sets were measured with the correct fit for the manikin (size L). Only one ensemble (WLF) was measured with size XL of turnout gear jacket. Both turnout gear of sizes L (correct size for manikin) and

XL, and bolero of size L were acquired from the fire station reporting the burn incidents. The turnout gear corresponded to EN 469 [21]. The turnout gear was dressed on top of the station wear corresponding to ISO 21942 [22] that had been measured earlier (set C2 with polo shirt with long arms in [1]). The station wear was of correct fit (size L) for the manikin.

Table 1. Images of the tested clothing ensembles (for items and composition see Tables 2 and 3). AL – nude manikin for air layer measurements; SK – manikin textile "skin" that was used in wetted state during evaporative resistance measurements; REC – ensemble often used during recovery near the incident site; WLF-L-B – ensemble for wildland firefighting, size L with bolero (the set with size XL jacket looked the same); TRW – ensemble used for technical rescue; WLF-L – ensemble for wildland firefighting, size L; WLF-XL – ensemble for wildland firefighting, size XL; SIF – ensemble for structural internal firefighting.



The other elements of the ensembles except turnout gear and bolero were the same items (helmets) or similar but not exactly the same, i.e. the same model, but a different item, or a new version of the garment model or not the same item but corresponding to the same standard, e.g. gloves, or of similar design, e.g. boxer shorts. The clothing items are listed and described in Table 2, and the items belonging to an ensemble are listed by codes in Table 3 together with the insulation and evaporative resistance results. Similar to the clothes worn during the incident and human testing, also the tested clothes were washed minimally 5 times.

Table 1 shows also the nude manikin (AL – air layer measurements), and textile skin (SK) that was wetted and contained about 1 kg water at the start of the evaporative resistance measurements. Part of the station wear can be seen in the ensemble combination REC in Table 1, but for full set view and description we refer to Kuklane et al. [1] as in this complementary study this set was not re-measured.

Locally available firefighter rubber boots of size 46 had to be used instead of proper size of firefighter leather boots as the boots sent for testing were this time completely new. These leather boots were too tight and stiff so it was not possible to dress them on manikin, while cutting was not allowed. Instead the measured insulation and evaporative resistances were re-calculated based on the boot values measured before [1] in order to match the real use in the Netherlands and for analysis of human studies. Still, in results' tables the original values measured with rubber boots are given for comparison (marked with #).

Table 2. List of used clothing items.

Nr.	Item and Their Variation Description	Brand, Model	Size, Version	Mass (g)	Materials	Notes
1a	Socks	Groenendijk, Brandweer Nederland	43–45	61.0		Similar to item 1 in [1]
4a	Rubber boots	Tretorn Koster	46	2759.5		Ensembles were tested with rubber boot, but in ensemble calculations were replaced with item 4 (firefighter boot, Haix, Fire flash gamma) in [1]
7a	Balaclava/fire hood		one size	104.0		Similar to item 7 in [1]
8a	Boxershorts (underwear)	Blaklader	XXL	122/110	92% cotton, 8% elastane	Similar design as item 8 in [1] but a different product
9a	T-shirt (underwear)	Narkonteks, Brandweer Nederland	L, regular	192/196	59% mode acrylic, 39% PimCotton, 2% elastane,	Similar to item 9 in [1]
10a	Belt (stretch-heavy)	Groenendijk		88		Similar to item 10 in [1]
12a	Polo shirt, long sleeves	Narkonteks, Brandweer Nederland	L, regular	442/442	60% Mode Acrylic, 40% Cotton, Pique, 200 g/m^2	Similar to item 12 in [1]
15a	Working trousers	SIOEN, Brandweer Nederland	52, regular	722/720	42% modacrylic, 29% cotton, 19% polyamide FR, 5% aramid, 4% elastolefin, 1% antistatic (AST) yarn	Similar to item 15 in [1]
16a	Safety gloves (cut resistant) for technical rescue	GUIDE, 313	10	74.0	Outer side raw material: Nitrile / palm dipped / micro foamed inner side raw material: single knitted / glass fibers / steel fibers / elastane / HPPE	Similar to item 16 in [1]
17a	Safety gloves (for structural firefighting)	Eska, Helios E; Tex Grip 3.0 – BA0912; v. 2022	10	282.0	Back of the hand: Nomex; palm: double knit Nomex/Kevlar with an elastic, flame-retardant silicone coating; liner: double knit carbon fiber / Kevlar – cut and heat protective	Different item but expected performance is similar to item 17 in [1]
21a	Firefighter jacket (corresponds to EN 469)	PWG	L+5	2080.0	OL: Twin Square ML: 100% aramid Water resistance: aramid/viscose/ high tech PU	Different item but expected performance is similar to item 21 in [1]
21b	Firefighter jacket (corresponds to EN 469)	PWG	XL+5	2208.0	OL: Twin Square ML: 100% aramid Water resistance: aramid/viscose/ high tech PU	Different item and size but general performance is expected to be similar to item 21 in [1] except the size effect (see [10])
22a	Firefighter trousers, standard model (corresponds to EN 469)	PWG	L, regular	1798.0	OL: Twin Square ML: 100% aramid Water resistance: aramid/viscose/ high tech PU	Different item but expected performance is similar to item 22 in [1]
25	Firefighter	Dräger, HPS	50–60	1622.0		The same as item 25 in [1]

	helmet	7000 H1				
26b	Face and neck cover (hollanddoek, connected to helmet (item 25), closed in front)	Dräger	one size	158.0		Similar to item 26 in [1]
26c	Face and neck cover (hollanddoek, connected to helmet (item 25), open in front, fixed at back side)	Dräger	one size	158.0		Similar to item 26A in [1]
27	Technical rescue helmet	MSA Gallet, F2 X-trem	52–64 cm	828.0		The same as item 27 in [1]
28a	Self-contained breathing apparatus (SCBA, no air, with frame)	Dräger, FPS 7000 + AirMaXX	One size	8720	Composite with 1 bottle rubber/plastic glass	Different item but expected thermal performance is similar to item 28 in [1] due to approximately similar frame coverage area of back
31c	Facemask	Dräger, FPS 7000		764		Different item but the same model as item in a set 31 in [1], to be fixed on helmet (25) and to be used with item 28a, similar expected thermal insulation as item 31A in [1]
32	Bolero		104	180		Used to discriminate specific persons, e.g. instructors, not measured in earlier study

3 Results and discussion

3.1 Clothing ensembles

The insulation and evaporative resistance of the ensembles can be seen in Table 3. The regional insulation and evaporative resistance vales are given in Tables 4 and 5, respectively. The values for the whole system are needed in various general (standard) and more simple prediction models [3,23,24], while detailed data on various body parts are useful for complex ones [3,5].

Table 3. Clothing ensembles and their properties (for images of the clothing ensembles see Table 1).

Code	Items in the Ensemble (See Table 1)	I_T m²K/W	f_{cl} n.d.	I_{cl} m²K/W	I_{cl} clo	$R_{et,raw}$ m²Pa/W	R_{et} m²Pa/W	R_{ecl} m²Pa/W	i_m n.d.	$i_{m,cl}$ n.d.
AL	Nude manikin (air layer insulation—I_a)	0.101	1.00	0.000	0.00					
SK	Manikin's textile skin (cotton)	0.131	1.03	0.033	0.21	12.8	9.3			
REC	1a, 4, 8a, 9a, 10a, 12a, 15a, 22a	0.249 (0.241#)	1.35	0.174	1.12		44.4*	33.0*	0.34*	0.32*
TRW	1a, 4, 8a, 9a, 10a, 12a, 15a, 16a, 21a, 22a, 27	0.370 (0.355#)	1.41	0.298	1.92	74.4#	68.3 (70.6#)	61.7	0.32	0.28
WLF-L	1a, 4, 8a, 9a, 10a, 12a, 15a, 17a, 21a, 22a, 26c (hollanddoek front open fixed to 25)	0.408 (0.381#)	1.42	0.337	2.17	87.2#	80.7 (83.4#)	74.2	0.29	0.25
WLF-LB	1a, 4, 8a, 9a, 10a, 12a, 15a, 17a, 21a, 22a, 26c (hollanddoek front open fixed to 25), 32	0.422 (0.396#)	1.42	0.351	2.27					
WLF-XL	1a, 4, 8a, 9a, 10a, 12a, 15a, 17a, 21b, 22a, 26c (hollanddoek front open fixed to 25)	0.429 (0.402#)	1.45	0.359	2.32					
WLF-XLB	1a, 4, 8a, 9a, 10a, 12a, 15a, 17a, 21b, 22a, 26c (hollanddoek front open fixed to 25), 32	0.418 (0.391#)	1.45	0.348	2.25					
SIF	1a, 4, 8a, 9a, 10a, 12a, 15a, 17a, 21a, 22a, 26b (hollanddoek front closed fixed to 25), 28a, 31c (fixed to 25)	0.435 (0.413#)	1.57	0.370	2.39	90.9#	84.6 (87.1#)	78.7	0.30	0.27

I_T — total clothing insulation; f_{cl} — clothing area factor; I_{cl} — basic clothing insulation; $R_{et,raw}$ — uncorrected total evaporative resistance; R_{et} — corrected total evaporative resistance; R_{ecl} — corrected clothing evaporative resistance; i_m — moisture permeability index; $i_{m,cl}$ — clothing moisture permeability index; # original values measured with rubber boots; * not measured, estimated based on ISO 9920.

Table 4. Clothing ensembles' local and regional clothing insulation values ($I_{T,i}$, $I_{T,z,i}$, m^2K/W).

Code	Head	Chest	Back	Abdomen	Buttocks	Torso	Upper Arms	Lower Arms	Arms	Hands	Thighs	Calves	Legs	Feet	Head, Hands and Feet Excluded
Area (m^2)	0.1329	0.1888	0.1929	0.0998	0.0844	0.5659*	0.1059^	0.0552^	0.3220*	0.0430^	0.1643^	0.1046^	0.5378*	0.1296^	1.4257*
AL	0.096	0.108	0.093	0.092	0.084	0.096	0.114	0.113	0.113	0.106	0.108	0.094	0.101	0.104	0.101
REC	0.091	0.271	0.203	0.555	0.527	0.285	0.232	0.210	0.223	0.116	0.486	0.440 (0.367$^{\#}$)	0.467 (0.430$^{\#}$)	0.346 (0.244$^{\#}$)	0.312 (0.306$^{\#}$)
TRW	0.129	0.514	0.518	0.952	0.906	0.600	0.547	0.343	0.443	0.150	0.498	0.430 (0.366$^{\#}$)	0.468 (0.435$^{\#}$)	0.346 (0.264$^{\#}$)	0.505 (0.490$^{\#}$)
WLF-L	0.191	0.430	0.510	0.795	0.763	0.536	0.539	0.307	0.420	0.323	0.459	0.440 (0.349$^{\#}$)	0.451 (0.408$^{\#}$)	0.346 (0.230$^{\#}$)	0.473 (0.454$^{\#}$)
WLF-LB	0.199	0.451	0.559	0.846	0.809	0.574	0.558	0.303	0.425	0.329	0.487	0.436 (0.371$^{\#}$)	0.465 (0.433$^{\#}$)	0.347 (0.230$^{\#}$)	0.491 (0.477$^{\#}$)
WLF-XL	0.197	0.485	0.543	0.893	0.877	0.592	0.555	0.334	0.444	0.346	0.484	0.437 (0.369$^{\#}$)	0.464 (0.430$^{\#}$)	0.346 (0.232$^{\#}$)	0.502 (0.486$^{\#}$)
WLF-XLB	0.190	0.483	0.561	0.866	0.798	0.591	0.555	0.299	0.421	0.327	0.467	0.434 (0.357$^{\#}$)	0.453 (0.416$^{\#}$)	0.345 (0.229$^{\#}$)	0.490 (0.473$^{\#}$)
SIF	0.282	0.479	0.557	0.744	0.624	0.558	0.474	0.308	0.391	0.343	0.488	0.440 (0.363$^{\#}$)	0.467 (0.429$^{\#}$)	0.346 (0.264$^{\#}$)	0.477 (0.461$^{\#}$)

* Total area of manikin zones in that body region; ^ mean area of symmetrical manikin zones; $^{\#}$ original values measured with rubber boots

Table 5. Selected clothing ensembles' local and regional total evaporative resistances (m^2Pa/W, correction acc. to Wang et al. [18]).

Code	All	Head	Chest	Back	Abdomen	Buttocks	Torso	Upper Arms	Lower Arms	Arms	Hands	Thighs	Calves	Legs	Feet	Head, Hands and Feet Excluded	Hands and Feet Excluded	Hands Excluded
SK	9.3	10.1	13.9	9.8	9.1	9.5	10.7	10.4	9.3	9.7	6.4	7.8	10.8	8.7	7.9	9.7	9.7	9.5
TRW	68.3 (70.6$^{\#}$)	15.3	226.1	87.6	258.7	185.1	142.6	87.8	77.7	80.9	26.7	85.4	83.8$^{\#}$	82.6$^{\#}$	107.0 (273.7$^{\#}$)	98.5$^{\#}$	71.7$^{\#}$	73.63 (76.3$^{\#}$)
WLF-L	80.7 (83.4$^{\#}$)	24.2	174.6	88.7	231.2	208.1	136.9	81.7	66.9	73.9	71.9	84.9	92.4$^{\#}$	86.0$^{\#}$	107.5 (219.1$^{\#}$)	96.8$^{\#}$	79.5$^{\#}$	81.23 (84.0$^{\#}$)
SIF	84.6 (87.1$^{\#}$)	53.3	174.3	90.4	193.3	144.2	128.5	71.0	55.4	64.1	69.6	84.1	79.3$^{\#}$	80.7$^{\#}$	105.4 (197.5$^{\#}$)	88.6$^{\#}$	84.1$^{\#}$	85.53 (88.2$^{\#}$)

$^{\#}$ original values measured with rubber boots

If we compare the clothing properties measured in this study with the previous one [1], then we see that insulation of a new system tends to be a bit higher for all incident scenarios (TRW, WLF and SIF) even when only one layer (C9A, C8) of the double jacket system is used (Fig. 1). On the contrary, evaporative resistance is higher for all VRK clothing systems than for the new sets corresponding to the same scenarios that were measured earlier [1].

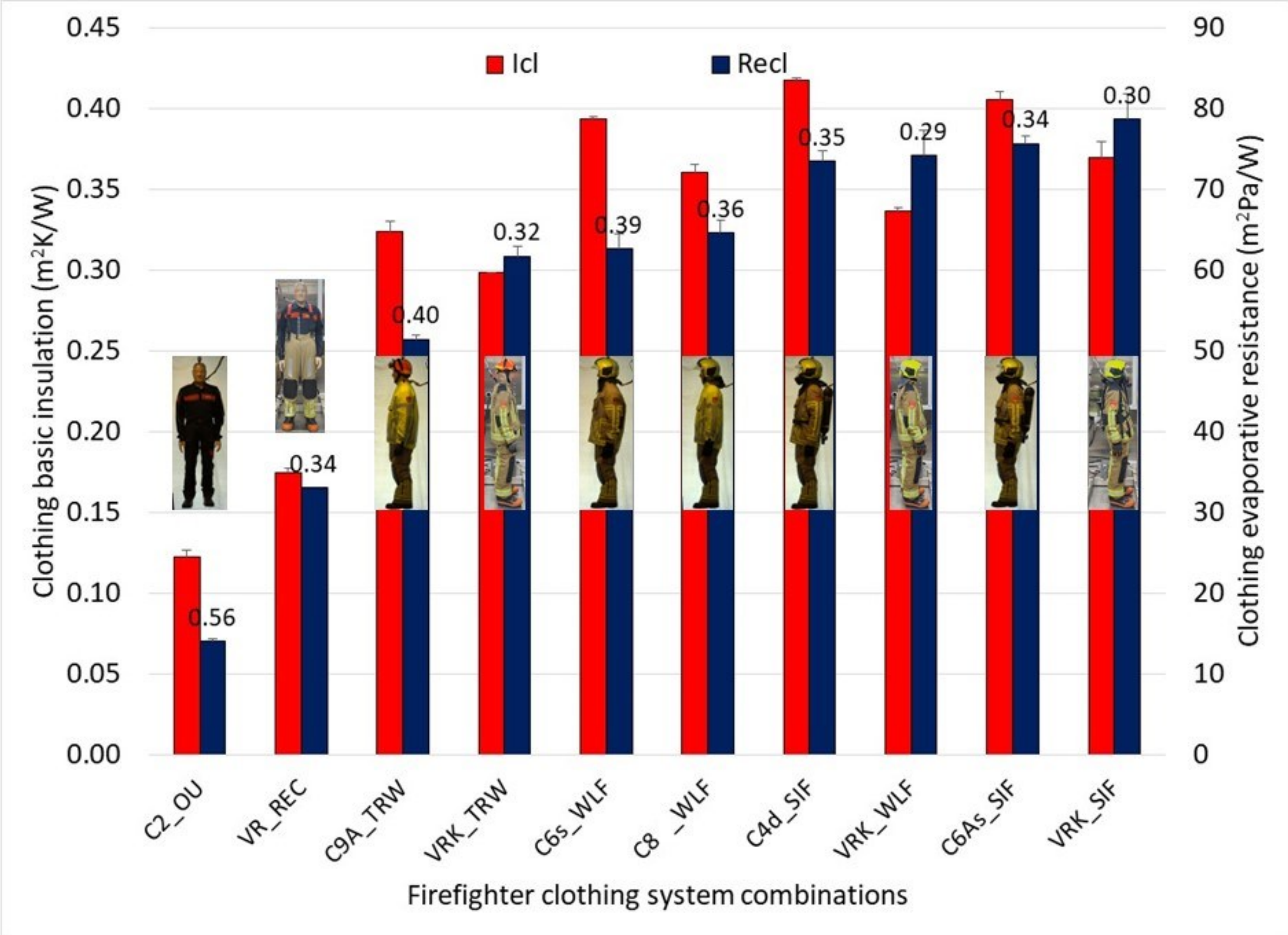


Fig. 1 Comparison of firefighter ensembles of this and previous study [1] that are meant to be or are used in the same incident scenarios. Results are sorted in ascending order for evaporative resistance. I_{cl} — basic clothing insulation; R_{ecl} — corrected clothing evaporative resistance. VR or VRK mark the ensembles of this study (VR_REC is average of 2 different turnout trouser models); C2_OU is a station uniform (operational uniform) measured in the previous study [1]; d or s specify if the ensembles of the previous study [1] use single jacket (s) or double layer jacket system (d) – the ones measured in this study (VRK) used all single layer jacket corresponding to EN 469 [21]. Values above the R_{ecl} bars represent moisture permeability index (i_m).

From the user perspective higher insulation is better for protection against extreme heat and radiation, while lower evaporative resistance contributes to better comfort when the body heat can be easier lost by evaporation. Thus, the new solution that was tested earlier [1] is expected to perform better and cause lower stress.

When judging ensembles for various purposes or incidents, it may be difficult to evaluate what may be better for the task, as the higher insulation commonly leads also to the higher evaporative resistance, for example, due to more material layers and air gaps [25]. Therefore cold protective clothing standard [13] sets the limits based on moisture permeability index (i_m) that utilizes the ratio between insulation and evaporative resistance. i_m values from 0.38 and above for normal clothes are considered having a good permeability, while lower values than that maybe connected with reduced sweat evaporation and comfort [15]. From the ensembles presented in Fig. 1, only C2 (station wear), C9A and C6s meet the criteria of good permeability (often also referred to as breathability) and the poorest values are for VRK sets. Material tests are important to specify protective properties of the material packages, however, it would be useful to start using moisture permeability index for judging over firefighter protective clothing thermal comfort performance as is done for cold protective clothing [13], but also other properties, e.g. air permeability, moisture transport and absorption capacity etc., that allow evaluating comfort [26].

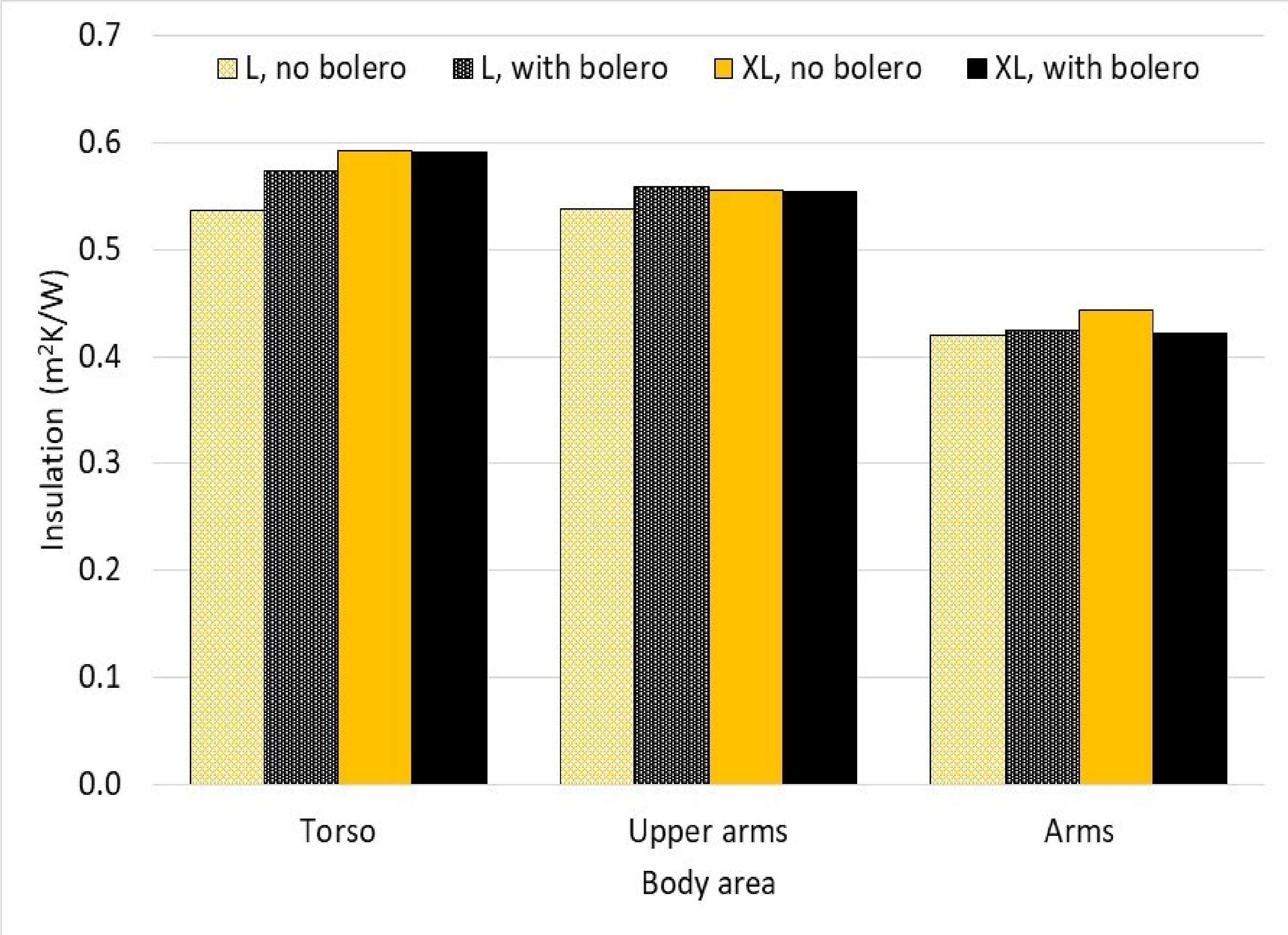


Fig. 2 Regional clothing insulation in 2 sizes (L and XL) of firefighter PPC ensembles without and with bolero.

3.2 Bolero use

In real use an instructor is using an additional layer of bolero on top of the jacket in the area of upper chest, upper back and upper arms (WLF-L-B in Table 1). Therefore, in Fig. 2 the focus is on the regional insulation of the protective clothing such as torso, arms and upper arms where direct influence of dressing bolero can be observed. Tables 6 and 7 show the percent differences between the sizes L and XL of the PPC ensembles, and between the sets without and with bolero, respectively. The results indicate an increase of the insulation in size L with bolero or no change or a slight reduction in size XL with bolero. The results are in line with earlier studies where the effect of size or fit was studied [6-11,27].

Different body areas may be affected differently, depending on how the accessory sits on the clothing but general trend is that size XL without bolero has higher insulation than size L (Table 6). Considering 4% as a significant difference, then torso and arms in XL had significantly higher insulation. At the same time, with bolero the difference between XL and L becomes negligible, while there is a considerable change in all these body areas showing that the values become closer, mainly due to insulation increase in size L clothing (Table 7). While significant insulation increase using bolero for size L occurs only in torso area, significant insulation decrease can be observed in XL for arms area only. The minimal increase of insulation in size L can also be observed in arms. This effect may be related to bigger initial air gap around upper part of lower arms that allows easier compression when using additional layers on top of it.

Table 6. Percentual insulation differences (%) between XL and L.

Bolero use	Torso	Upper arms	Arms
Without bolero	9.9	3.1	5.5
With bolero	3.0	-0.6	-0.9

Table 7. Percentual insulation differences (%) between conditions with and without bolero.

Size	Torso	Upper arms	Arms
L	6.7	3.6	1.2
XL	-0.2	0.0	-5.2

3.3 Occupational safety implications

The affected person was also interviewed. Answers to background questions related to the tasks and day description with the description what happened follow below:

> *(He) was the stoker, built up without a fire suit and already in the afternoon. // On the evening itself, because of the first time there, we took a tour with the stokers and instructors and how we are going to build it up and what the learning objectives are. // Had on long-sleeved thermal clothing with a T-shirt. I also had a bolero on over the fire jacket as extra protection. // During the first exercise when lighting, I was put inside to see if it developed well in the beginning and beyond. // Then very briefly 2 times after inside to close the connecting door and outside again. // After exercise 1 cooled back for the build-up of exercise 2. // Not really strained and not really sweaty.*
>
> *Was a pile of smoldering and some flames of about 40 cm high. The intention was to use 2 pallets and 2 large chipboards. It felt warm to the touch when the first chipboard was placed against the side wall in the appropriate brackets. (Was not above the firebox, about 1.5 Distance.) // 2nd plate taken from another room. With the intention of placing it above the fire in the holder. // When entering the fire room, the turnout suit started to break. Put down the plate and immediately go outside (distance to the firebox 4 meters. // Outside, they continue to burn through the suit. // Also after previous experiences I deliberately opted for a fire suit with a larger size for more air and space in the suit.*

It has to be considered that the manikin is of the same size either when using L or XL. However, if the user of XL size himself is bigger then there is no additional air layer to compress, and compression by bolero would not just reduce air space between the layers, but also more of the material packages themselves, meaning that the negative effect of compression might have been even stronger than seen on the manikin. Thus, instead of increasing the insulation with bolero in that case would translate into stronger effect of insulation reduction. If a user was aware of his prolonged exposure to heat and radiation during exercise and selected even a number larger jacket, i.e. XXL, then under a bolero of size L there would have occurred even higher compression of the material packages. If the compression affects skin tissues, then a negative effect may be amplified also by reduced blood circulation to the specific body areas.

During the incident the person was working in heat and carrying materials. This would mean that the upper arm (biceps) had been under tension, and a 1.6 cm wider diameter of upper arm compared to arm in relaxed position (0.8 cm compared to manikin). When working in heat for some time already with clothing layers becoming hot, then an additional compression of the layers (0.8 cm unidirectional, assuming circular cross-section) could have led to the reported incident. Thus in the adverse event analysis also the body postures need to be considered [28], but also dynamics of changing of postures from one to another [29] and in specific cases also body morphology [30]. Another factor that may have influenced such situation is the accumulated moisture (sweat), although the affected person did not notice especially wet clothes. The person had worked already for some time and at least some sweating was present due to work and heat exposure. If the clothing layers become wet then the compression allows even quicker heat transfer from hot outer layers to the skin.

4 Conclusions and limitations

This study provides basic information on firefighter clothing properties that can be used for exposure prediction, but also for validating various more or less advanced thermo-physiological models if human data on comparable clothing systems is available. It also demonstrates the value of acquiring regional thermal properties as it adds a dimension of clothing physical performance to adverse events' investigation. This study supports the reasoning that compression of the layers due to a mismatch in sizes of a combination of clothing sizes is a reason for higher thermal risks during the exposure, while a correct size or slightly bigger clothing item over outer layer reduces such risks. The outcome has practical implication as a recommendation not to use small size garment elements on top of the protective clothing set. However, the other possible reasons for the particular incident, e.g. certain sudden changes in environment, cannot be ruled out. This was a limited study where only insulation of sizes L and XL without and with bolero of size L were tested on a standing thermal manikin. It would be of interest to test also a correct fit ensemble (size L for manikin) with a smaller size (M) of bolero, to estimate insulation reduction in this case, but also study the effects of moisture (sweat) in the clothing and the dynamic conditions (walking manikin). Also, the materials' properties of the suit were not tested. It was only known that all relevant parameters corresponded to the standard, but no specific values were available to be put in context of the manikin results and incident description.

Author Contributions

KK and RH – conceptualization, discussions, review and revision; KK – methodology, visualization, writing, supervision; KK, AMHK, LMGJ – investigation, data curation, analysis. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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