(REFEREED RESEARCH)

ANALYSIS OF THERMAL PROPERTIES OF FIREFIGHTER’S PROTECTIVE CLOTHINGS

İTFAİYECİ KORUYUCU KIYAFETLERİNİN ISIL KONFOR ÖZELLİKLERİNİN ANALİZİ

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ABSTRACT

Working environments of firefighters is very dangerous and consist of multiple threats. Fire protection can be achieved by wearing firefighters’ clothing that is produced from multilayered textile materials. This layered structure prevents good ventilation, creates high heat stress to the wearers and reduces their working efficiency in fires. In this study, two types of outer shell fabrics, two types of moisture barrier fabrics with membrane and two types of thermal barrier fabrics that are used in the firefighter’s clothing production were tested for their thermal comfort properties. It was carried out objective fabric tests to determine the thermal conductivity, thermal diffusivity, thermal absorptivity, water vapor resistance, air permeability and moisture permeability properties. Also, two firefighter uniform models with PBI (Poly-benzimidazole)/ Para-Aramid and Nomex outer shell produced using these fabrics were evaluated using thermal camera to analyze the thermal distribution in different areas under the same environmental and physical conditions.

Keywords: Protective clothing, comfort, firefighters' clothing

ÖZET

İtfaiyecilerin çalışma ortamları çok tehlikeli olup birçok tehdit içermektedir. Yangından korunma çok katmanlı tekstil malzemelerinden üretilmiş itfaiyeci giysileri giyerek sağlanmaktadır. Bu katmanlı yapı iyi havalandırmayı önler, kullanıcılar için yüksek ısı stresi yaratır ve yangın esnasında çalışma verimini düşürür. Bu çalışmada, itfaiyeci giysisi yapımında kullanılan iki tip dış katman, iki tip membran içeren nem bariyeri ve iki tip ısıl bariyer kumaşın konfor özellikleri test edilmiştir. Isıl iletkenlik, ısıl difüzyon, ısıl absorplama, su buharı direnci, hava geçirgenliği ve su buharı geçirgenliği özelliklerini belirlemek için objektif test metodları kullanılmıştır. Ayrıca seçilen kumaşlardan üretilmiş PBI (Poly-benzimidazole)/ Para-Aramid ve Nomex dış katmanlı aynı model iki itfaiyeci kıyafeti, aynı çevre koşullarında ve fiziksel aktivite koşullarında, termal kamera kullanılarak giysi üzerinde farklı bölgelerde oluşan ısıl dağılım değerlendirilmiştir.

Anahtar Kelimeler: Koruyucu kıyafet, konfor, itfaiyeci giysisi

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1. INTRODUCTION

Protection together with comfort is very important subject for the performance of protective equipment. Firefighting is very dangerous work and today firefighters wear personal protective equipment to protect themselves during their highly dangerous work. Also they have to perform their jobs under very restrict time intervals so their motion and working performances are highly dependent on clothing comfort. The balance of thermal protection from fire and metabolic heat stress generated by the human body due to metabolic activities are very important during fire situations. The structure of the garments must allow evaporation of perspiration, ventilation and also thermal protection from fire.

In fire situations, fabrics are subjected to extremely heavy loads. Fabric performance in these situations is related to comfort, time, heat, durability, and other characteristics specific to the occurrence [1]. Moreover the thermal performance of fire fighters' protective clothing is primarily based on the thermo-physical properties of the materials used to construct the clothing. The physical properties used for thermal analysis and predictions are: thermal conductivity, specific heat, density, and the thermal spectral properties of emissivity, transmissivity and reflectivity [2]. Vettori reported thermal conductivity data for ten materials used in fabricating fire fighters' protective clothing that included outer shell fabrics, moisture barriers, and thermal liner battings. Materials were tested twice for the thermal conductivity data, when they were new and after they were conditioned. [2]. Holcombe explained the heat related properties of protective clothing fabrics [3]. Lawson and Pinder gave estimates for the thermal conductivity of 10 different materials used in the construction of fire fighters' protective clothing [4]. A serious potential concern for firefighter protective clothing is the temperature transmission through the fabric which is normally tested by the thermal protective performance tests on dry fabrics. Hirschler studied the effect of dampness and compared the temperature transmission values of two fabrics (aramid and modified viscose) to decide the suitable one as the protective outer fabrics for firefighter turn-out coats [5]. Sun et. al. investigated the radiant-heat thermal protection and comfort performance of wild land firefighters clothing measuring air permeability, vapor evaporation, and thermal resistance of single-layer fabrics. They also discussed the impact of color differences of outer layers, their thickness or weight, and their structural features on radiant protective performance values and thermal resistance [6]. Barker et. al. searched the effects of absorbed moisture on the thermal protective performance of the fire fighter turnout materials exposed to a low-level heat source. They found a complex influence of absorbed moisture on the protective performance of fire fighter turnout systems [7]. Holmér explained protective clothing in hot environments. He considered the protective clothing against heat and chemical agents and investigated their effects on the thermal balance and performance [8].

Chung and Lee, studied comfort properties of protective clothing for firefighters and they suggested that the system of clothing design and material layers must be chosen carefully to balance protection and comfort [9]. Wang et al. concluded that the special clothing ensembles that firefighters wear should provide not only thermal protective performance but also thermal and moisture-related comfort. The comfort property of protective clothing has great influence on work efficiency [10]. Mah and Song outlined that firefighting clothings' heat and moisture transfer capacity was affected by many factors, such as material properties, style, fit, size and drape of garments [11]. Raimundo and Figueiredo found that it was possible to enhance firefighter safety by the augmentation of clothing insulation and vapour permeability efficiency. Li et al. evaluated the effects of material component and design feature on heat transfer in firefighter turnout clothing [12]. Lawson and Vettori, suggested that firefighters protective clothing' thermal performance must be evaluated while dry, when wet, in full loft and when fully compressed [13]. According to Lawson et al., thermal performance of fire fighters' protective clothing was primarily based on the thermo-physical properties of the materials that were used to construct the clothing and the insulating air space that was provided by the garment design[14]. Wakatsuki et. al. investigated if the synthetic underwear plays a significant role in moisture and metabolic heat transfer within the fire fighter clothing [15]. He et. al. showed the heat and moisture transport performance of the multilayer protective clothing under seven different ambient conditions [16]. Fu et. al. have tested two kinds of protective clothing with different vapor permeability in order to study the design influence on protective properties[17].

In this study, it is aimed to analyze some thermal comfort properties of different types of outer shell fabrics, moisture barrier fabrics and thermal barrier fabrics that are mostly used in the firefighter's clothing production. Two types of outer shell fabrics, moisture barrier fabrics and thermal barrier fabrics were combined to make a multilayered fabric assembly for firefighter suits. Thermal conductivity, thermal diffusivity, thermal absorptivity, water vapor resistance, water vapour permeability, air permeability analyses were conducted to test the comfort properties of the fabrics. Moreover, thermal comfort performances of two kinds of firefighter uniforms were evaluated using thermal camera and heat distribution of different areas under the same environmental and physical conditions was evaluated.

2. MATERIAL AND METHOD

2.1. Materials

Two different outer shell, moisture barrier and thermal barrier fabrics made of para-aramide, meta-aramide blend FR material are selected for the experiments shown in Table 1. Moisture barrier fabrics were laminated using hot-melt lamination technology. Water-jet nonwoven fabric and weft knitted fabric were used.

Two firefighter uniforms having the same design and produced using different types of materials were tested with thermal camera for their thermal performances. The firefighter uniforms were produced according to *EN 469:2005 "Protective clothing for firefighters. Performance requirements for protective clothing for firefighting"* standard and *EC directive 89/686 EEC personal protective equipment*[18,19]. In Figure 1 and 2 firefighter clothings are shown.

Table 1. Fabric properties

Fabric Code	Fabric Type	Mass per unit area (g/m^2)	Layer Type
A1	Nomex® Outershell Tough	195	Outer Shell
A2	40% PBI / 60% Para-Aramid	200	Outer Shell
B1	PU membrane laminated to FR Knitted Fabric	145	Moisture Barrier
B2	PU membrane laminated to FR Nonwoven	125	Moisture Barrier
C1	Aramid felt quilted to Aramid/Viscose FR fabric	245	Thermal Barrier
C2	Two layers of FR Nonwoven quilted to Aramid/ Viscose FR inner lining	225	Thermal Barrier

Table 2 shows the materials used for the firefighter clothings. Firefighter clothings consist of three layers; outer shell, moisture barrier and thermal barrier. Two types of firefighter clothings having same design properties were selected for the experiments. They have 60 cm zipper in front of the jacket with quick release system, concealed by a storm flap, closes with FR Velcro fastener. Throat closure tab located under the collar and there is radio pocket. Aramid knitted cuffs on the jacket designed to prevent liquids and burning particles to go through it. Anti-wicking strips at the hem of the jacket and trousers, elastic belts on the right and left of the waist, elastic and adjustable braces on the trousers, and reflective tapes with aramid backing were used. 100% aramid sewing threads are used during sewing layers and all waterproof seams are fully sealed with the seam sealing tape. Firefighter clothing sizes are specified according to EN 340 [20].

Selected firefighter clothings were produced using different materials in different layers. The outer shell of type 1 clothing was made of Nomex®, for type 2 firefighter clothing it was produced using 40% PBI (Poly-benzimidazole) / 60% Para-Aramid blend fibers. The second layer, moisture barrier, was selected PU membrane laminated to FR knitted fabric in type 1 clothing and polyurethane (PU) membrane laminated to fire resistant (FR) nonwoven in type 2 firefighter clothing. The third layer, the thermal barrier, aramid felt quilted to aramid/viscose FR fabric was used in type 1 clothing and two layers of FR nonwoven quilted to aramid/ viscose FR inner lining was used in type 2 clothing.

2.2. Methods

In this study Alambeta was used to test thermal properties of the fabrics. Permetest instrument was used to measure water vapour resistance and water vapour permeability according to the ISO 11092:2014 Textiles -- Physiological effects -- Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test) standard (Figure 4)[21]. Standard Test Method for Air Permeability of Textile Fabrics according to ASTM D737-96 was applied for testing samples. [22]. Testo 885-1 thermal camera was used to measure the thermal distribution behaviour of garments. Testo 885-1 is a handy and robust thermal imager. It enables to carry out contactless determination and display of the temperature distribution on surfaces. It has a hi-resolution camera with resolution of 320 x 240 pixels, thermal sensitivity of less than 30 mK, 30° standard lens, minimum focusing distance of 0.1 m, manual and auto focus, touchscreen, built-in digital imager with power LEDs for illumination [23].

A simple wear test was designed considering the studies in literature [24,25]. Exercises with firefighter uniforms were performed in two consecutive days at the fitness center on the running tape. The exercise time of the day was selected as the same for two days, which was 10.30 a.m. Also the environmental conditions were the same for these days that was 24 ^{o}C and 55% R.H.. A person who is 27 years old was selected for testing the clothing. He firstly walked 5 minutes at the speed level of 5 km/hour. Then, he run again 5 minutes at the speed of 10 km/hour. Before and after the exercise, pictures with thermal camera were taken.

Table 2. The fabric layers of firefighter clothings

Firefighter Clothing Type	Fabric Layer Type	Fabric Code	Fabric Details
Firefighter Clothing Type 1	Outer Shell	**A1**	Nomex® Outershell Tough
	Moisture Barrier	**B1**	PU membrane laminated to FR Knitted Fabric
	Thermal Barrier	**C1**	Aramid felt quilted to Aramid/Viscose FR fabric
Firefighter Clothing Type 2	Outer Shell	**A2**	40% PBI / 60% Para-Aramid
	Moisture Barrier	**B2**	PU membrane laminated to FR Nonwoven
	Thermal Barrier	**C2**	Two layers (55+55 g/m^2) of FR Nonwoven quilted to Aramid/ Viscose FR inner lining

Figure 1: Firefighter clothing Type 1

Figure 2: Firefighter clothing Type 2

3. EXPERIMENTAL RESULTS

3.1. Thermal Comfort Test Results

Thermal comfort test results are given in Table 3.

Table 3. Thermal Comfort test results of fabric types

Fabric Code	Thermal Conductivity	Thermal Diffusivity	Thermal Absorptivity	Thermal Resistance	Thickness	Relative water permeability	Water Vapour Resistance
	(W/m.K)	(mm^2/s)	($W.s^{-1}/m^2.K$)	($mK/W. m^2$)	(mm)	(%)	($Pa.m^2/W$)
A1	32.40	0.0267	201.10	11.20	0.3690	63.37	3.47
A2	35.20	0.0337	192.43	11.10	0.3930	65.53	3.17
B1	30.90	0.0273	190.27	14.10	0.4347	63.50	3.80
B2	30.23	0.0733	112.30	23.93	0.7263	65.70	3.20
C1	34.63	0.1777	82.43	47.20	1.6353	55.10	4.97
C2	33.80	0.2287	69.60	66.57	2.2497	50.40	5.93
A1B1C1	40.40	0.0980	130.23	66.80	2.7200	21.20	22.30
A2B2C2	40.00	0.1373	108.63	86.70	3.7900	26.03	17.93

Figure 3 shows thermal conductivity results of fabric types. Thermal conductivity indicates the ability of a material to conduct heat. For outer shell fabrics, thermal conductivity value was lower for **A1** than **A2**. On the other hand, moisture barrier fabric **B2** and thermal barrier **C2** had lower conductivity values than **B1** and **C1**. Although thermal conductivity value of **A2** was higher than **A1**, fabrics **B1** and **C1** had higher thermal conductivity and this leaded to a small difference between the thermal conductivity values in multilayered structures of **A1B1C1** and **A2B2C2**.

Thermal conductivity is measured considering a steady-state, linear flow of heat through the material. On the other hand, **thermal diffusivity** prevents errors arising from the non-realization of the boundary and steady-state conditions and remove the steady state condition by measuring temperature as a varying function of time [26]. It measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. This value describes how quickly a material reacts to a change in temperature. The higher the thermal diffusivity, the faster the heat propagation. According to the results, it is clearly seen that the thermal diffusivity of fabrics **A2, B2** and **C2** had higher values than **A1,B1** and **C1** (Figure 4). As a result, three layered structure **A2B2C2** showed higher diffusivity value than **A1B1C1**.

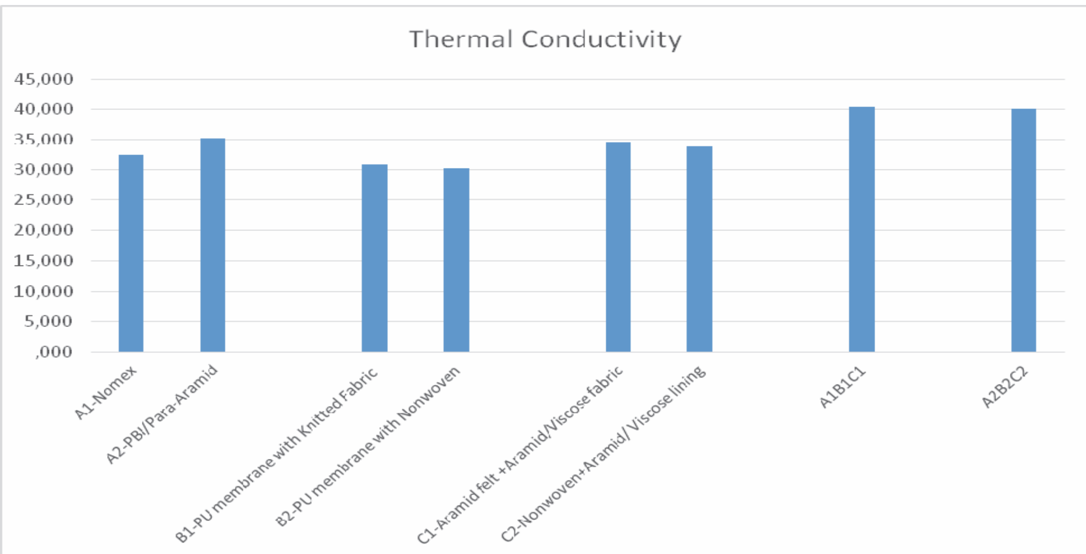

Figure 3: Thermal conductivity of fabrics

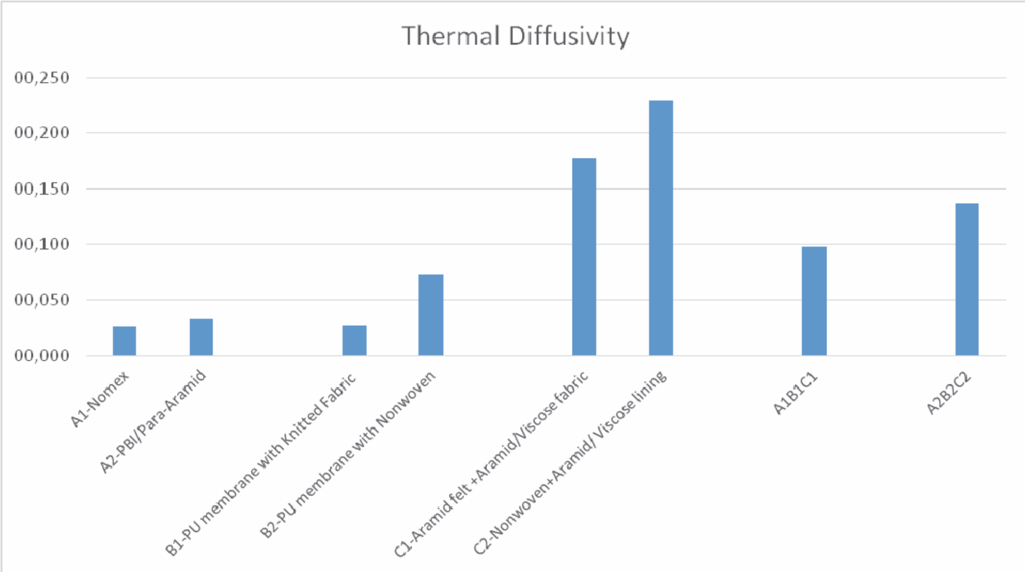

Figure 4: Thermal diffusivity of fabrics

Thermal resistance is inversely proportional to thermal conductivity. Higher thermal resistance leads to higher thermal insulation in fabrics. Figure 5 shows the thermal resistance results of single layered and multi-layered fabrics. A1 and A2 had nearly the same thermal resistance values. Thermal resistance of fabrics **B2** and **C2** have been found higher than **B1** and **C1**. As a result, three layered structure **A2B2C2** had higher thermal resistance value than **A1B1C1** because it had two layers (55+55 g/m2) of FR Nonwoven quilted to Aramid/ Viscose FR inner lining.

Thermal absorptivity gives the warm-cool feeling of fabrics. Thermal absorptivity is higher for **A1,B1,C1** and lower for A2,B2 and C2 (Figure 6). Three layered structure **A1B1C1** had higher thermal absorptivity than **A2B2C2** and as the thermal absorptivity of **A1B1C1** was higher, a cooler feeling at first contact was felt.

Water vapour permeability is the ability to transmit vapour from the body. Figure 7 shows the relative water vapour permeability values. As it can be seen from the results, **A2, B2** and **C1** had higher water vapour permeability values. Moreover, three layered structure of **A2B2C2** had higher permeability than **A1B1C1**.

Water vapour resistance gives the resistance value of a fabric to transmit water vapour. If the water vapour resistance is high, water vapour cannot be transmitted through the layers of fabrics and causes an uncomfortable feeling. Fabric types, **A2** and **B2** had lower water vapour resistance values than **A1** and **B1** and this leaded lower resistance value for the three layered fabric structure of **A2B2C2** although it has thicker thermal barrier fabric and more comfortable feeling.

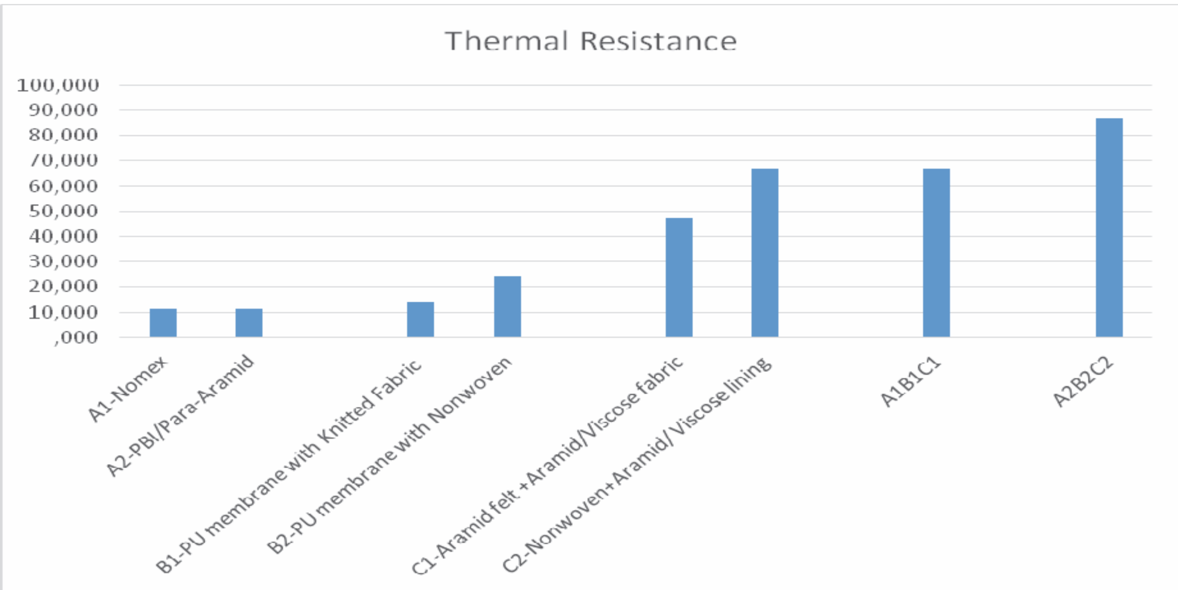

Figure 5. Thermal resistance of fabrics

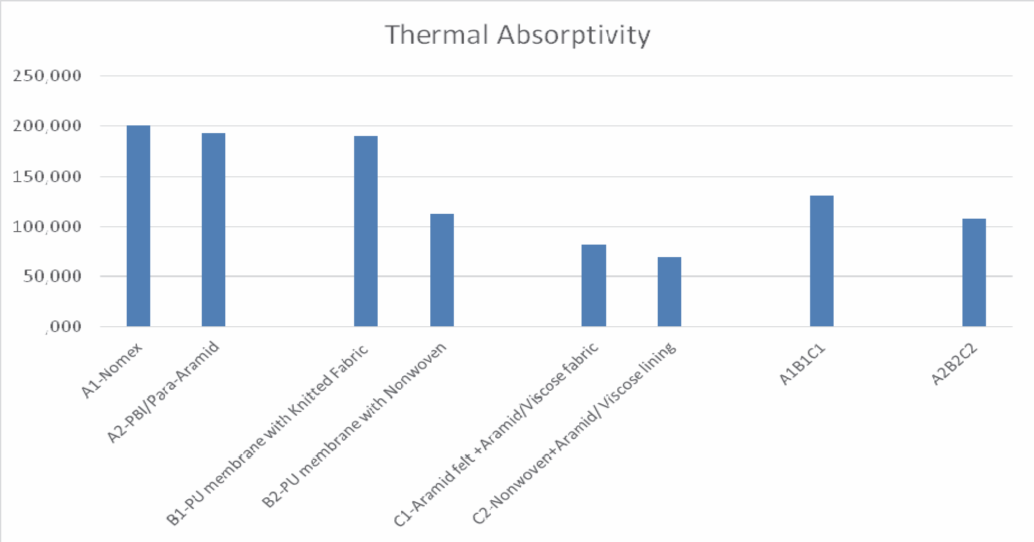

Figure 6: Thermal absorptivity of fabrics

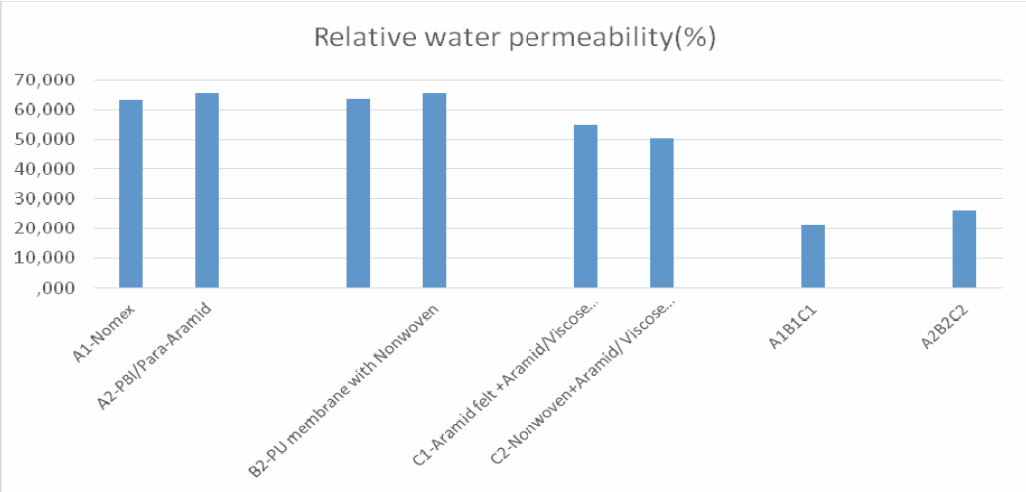

Figure 7: Relative water vapour permeability of fabrics

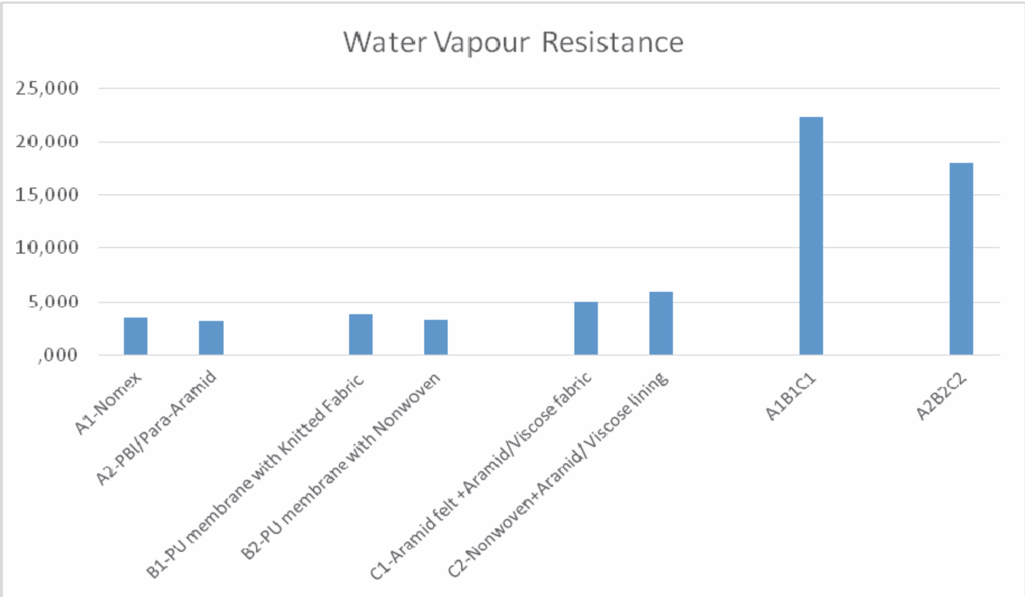

Figure 8: Water vapour resistance of fabrics

Additionally air permeability was measured for all fabric types and found that all of the moisture barrier fabrics do not permit the air transmission because of the membrane.

3.2. Statistical Analysis for Thermal Comfort Tests

Statistical analyses were conducted using IBM SPSS 23 statistic programme. It was found high correlation values between thermal conductivity, thermal diffusivity, thermal absorptivity, thermal resistance, water vapour permeability and water vapour resistance (Table 4).

Paired sample t-test procedure was applied to test the relationships between variables. It was found a significant relationship between the pairs of thermal conductivity, thermal absorptivity, thermal diffusivity, thermal resistance, water vapour resistance and water permeability and thickness (Table 5).

Table 4. Correlation values between measurements

Outer Shell Fabrics	Correlation
Thermal_conductivity & Thermal Diffusivity	0.756
Thermal_conductivity & Thermal Resistance	-0.737
Thermal Absortivity& Thermal Diffusivity	-0.850
Thermal_conductivity & Thickness	0.828
Thermal Diffusivity& Thickness	0.705
Water vapour resistance & Thickness	-0.729
Water permeability & Thickness	0.725
Water permeability & Water vapour resistance	-0.988

Moisture Barrier Fabrics	Correlation
Thermal Diffusivity& Thermal Absortivity	-0.981
Thermal Diffusivity& Thermal Resistance	0.887
Thermal Absortivity& Thermal Resistance	-0.893
Thermal Diffusivity& Thickness	0.919
Thermal Resistance&Thickness	0.996
Thermal Diffusivity& Water vapour resistance	-0.766
Thermal Absortivity& Water vapour resistance	0.788
Thermal Resistance& Water vapour resistance	-0.915
Water vapour resistance & Thickness	-0.908
Water permeability& Water vapour resistance	-0.596

Thermal Barrier Fabrics	Correlation
Thermal_conductivity & Thermal Resistance	-0.658
Thermal Diffusivity& Thermal Absortivity	-0.918
Thermal Diffusivity& Thermal Resistance	0.691
Thermal Absortivity& Thermal resistance	-0.824
Thermal conductivity & Thickness	-0.602
Thermal Diffusivity&Thickness	0.715
Thermal Absortivity&Thickness	-0.831
Thermal Resistance&Thickness	0.997

Table 5. Hypothesis test results of fabrics

Paired Samples Correlations and significance levels of outer shell fabrics			
		Correlation	Sig (2-tailed)
Pair 1	Thermal conductivity &thickness	0.828	0.000
Pair 2	Thermal diffusivity &thickness	0.705	0.000
Pair 3	Water permeability&thickness	0.725	0.000
Pair 4	Water vapour resistance &thickness	-0.729	0.000

Paired Samples Correlations and significance levels of moisture barrier fabrics			
		Correlation	Sig (2-tailed)
Pair 1	Thermal diffusivity &thickness	0.919	0.000
Pair 2	Thermal absorptivity &thickness	-0.929	0.000
Pair 3	Thermal_resistance & thickness	0.996	0.000
Pair 4	Water vapour resistance &thickness	-0.908	0.000

Paired Samples Correlations and significance levels of thermal barrier fabrics			
		Correlation	Sig (2-tailed)
Pair 1	Thermal conductivity &thickness	-0.602	0.000
Pair 2	Thermal diffusivity &thickness	0.715	0.000
Pair 3	Thermal absorptivity &thickness	-0.831	0.000
Pair 4	Thermal_resistance & thickness	0.997	0.000

Independent samples T Test procedure was used to compare the differences between means of fabric types considering thermal comfort results. For **outer shell** fabrics, it was found a difference between the means of A1 and A2 fabrics for thermal conductivity values [Sig.(2-tailed)=0.015]. When **moisture barrier fabrics** considered, it was obtained that there is significant difference for thermal diffusion [Sig.(2-tailed)=0.004], thermal absorption [Sig.(2-tailed)= 0.006], thermal resistance [Sig.(2-tailed)=0.00] and water vapour resistance [Sig.(2-tailed)=0.021] values. For **thermal barrier** fabrics, zero hypothesis (there is no difference between the means of thermal barrier fabrics) was rejected for thermal absorption [Sig.(2-tailed)=0.016] and thermal resistance [Sig.(2-tailed)=0.04] values.

3.3. Thermal Camera Test Results

Thermal camera was used to test the heat distribution in firefighter clothing during use. Figures 9-12 shows the heat distribution histograms for firefighter uniforms, type 1 and type 2, before and after the exercises.

Figure 9 shows the heat distribution histogram of the firefighter clothing type 1 before the exercise and Figure 10 shows the heat distribution histogram of firefighter clothing type 1 after the exercise. As it is seen from the figures, before exercise maximum body temperature is 23.3 ^{o}C and after exercise it reached to 29.3^{o}C. Also the heated areas were especially underarms, neck and shoulders around the chest and shank area.

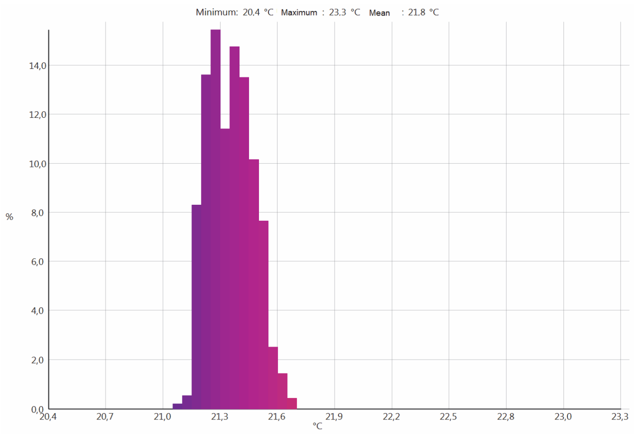

Figure 9. Heat distribution histogram of firefighter clothing type 1 before exercise

Figure 11 shows the heat distribution histogram of the firefighter clothing type 2 before exercise and Figure 12 shows the heat distribution histogram of the firefighter clothing type 2 after exercise. As it is seen from the figures, before exercise maximum measured temperature was 25.2 ^{o}C and after training it reached to 28.3 ^{o}C for the clothing type 1. Mean value for temperature was increased from 21.2 to 22.6 ^{o}C. Temperature increase was observed especially around underarms, neck, shoulders around the chest and shank area.

It is seen from the Figure 13 that, type 1 firefighter clothing had reached to a higher temperature level (29.3 ^{o}C) than the type 2 clothing (28.3 ^{o}C) after the exercise. Moreover after the exercise, the person had a lower mean temperature (22.6 ^{o}C) in type 2 uniform than the type 1 uniform (24.1 ^{o}C).

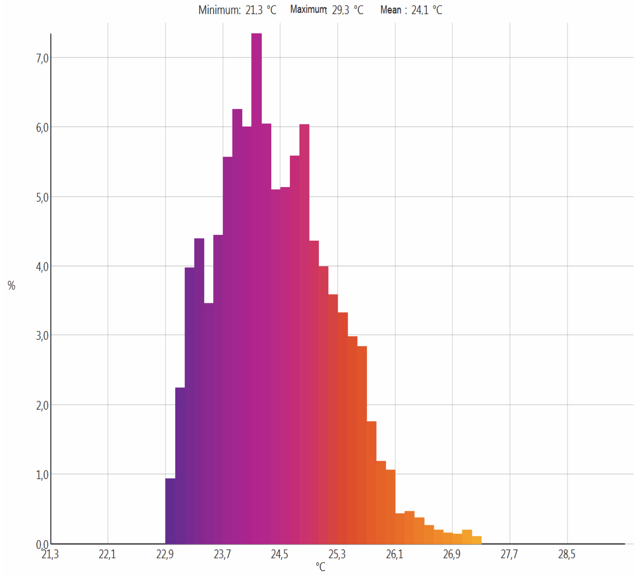

Figure 10. Heat distribution histogram of firefighter clothing type 1 after exercise

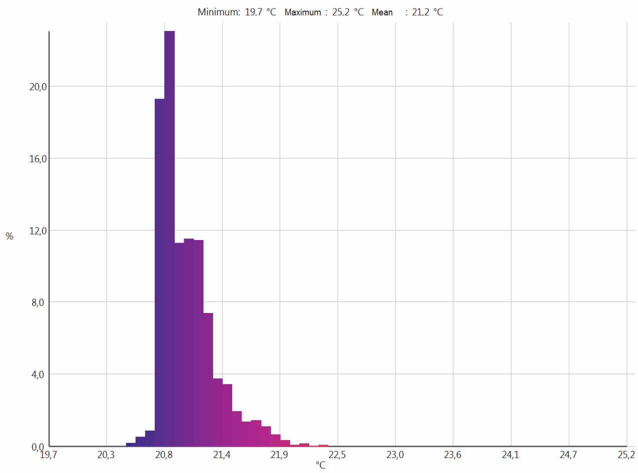

Figure 11. Heat distribution histogram of firefighter clothing type 2 before exercise

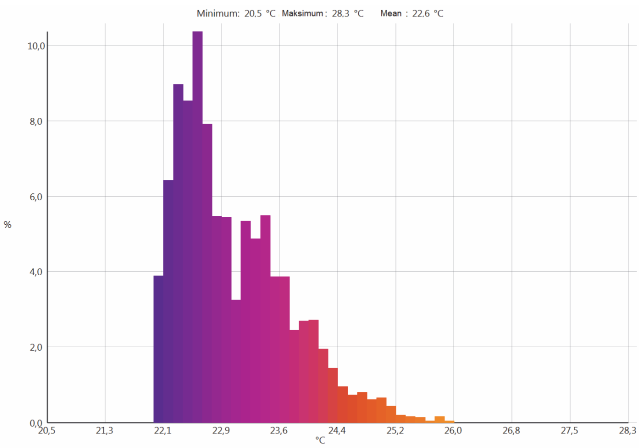

Figure 12. Heat distribution histogram of firefighter clothing type 2 after exercise

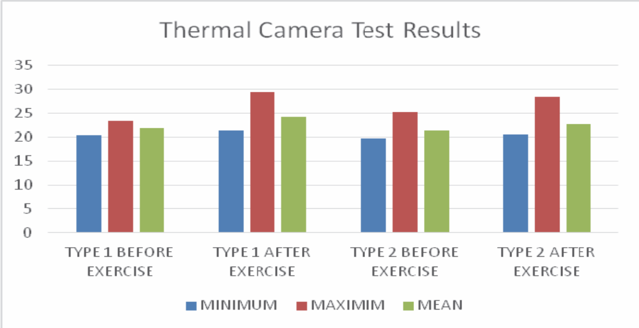

Figure 13. Thermal camera results of firefighter clothings

Single layer fabric test results are very important to understand multi-layered fabric construction behavior. When experimental results for outer shell fabrics were considered, it was seen that A2 had higher thermal conductivity, thermal diffusion and water vapour permeability values but lower thermal absorption, thermal resistance and water vapour resistance values. When moisture barrier fabrics investigated, it was seen that B1 had higher thermal conductivity, thermal absorptivity and water vapour resistance and lower thermal diffusivity, thermal resistance and water vapour permeability. Thermal diffusivity, thermal resistance, water vapour resistance values were higher and thermal conductivity, thermal absorptivity, water vapour permeability were lower for C2 thermal barrier fabrics.

When multi-layered fabrics considered the results showed some differences due to the change in outer shell, moisture barrier and heat barrier fabrics. Fabric tests for multi-layered structures clearly showed that, **thermal conductivity** values mainly influenced by moisture barrier and thermal barrier fabrics which are higher for type 1 clothing. **Thermal diffusion** for multi-layered structure is lower for A1B1C1 and when we looked single layered fabric results, these was not an unexpected result because all single layer fabric types in type 1 clothing had lower thermal diffusivity values. Moreover for **thermal absorptivity**, all single layered fabric types used in type 1 firefighter clothings had higher thermal absorptivity values than type 2 clothing and this concluded multi-layered fabric structure of A1B1C1 having higher thermal absorptivity value than A2B2C2. Although **thermal resistance** values of A1 and A2 were very similar, B1 and C1 had lower values so A1B1C1 had lower thermal resistance than A2B2C2 due to moisture barrier and heat barrier fabrics. **Water vapour resistance** values of outer shell A2 and moisture barrier B2 fabrics were lower and layered structure A2B2C2 had lower Ret value. Furthermore **water vapour permeability** is higher for A2B2C2 which was mainly influenced by outer shell and moisture barrier fabrics.

Type 2 clothing has higher mass and thickness compared with Type 1 and this yielded to higher thermal resistance and lower thermal conductivity performances. On the other hand, type 2 clothing had better water permeability, moisture permeability, thermal diffusion and absorption properties and this resulted better comfort performance than type 1 clothing. Moreover, a result of thermal camera measurements it was obtained that type 2 firefighter clothing showed better performance than type 1 clothing.

4. CONCLUSIONS

The thermal performance properties of firefighters' protective clothing are primarily based on the thermal comfort properties such as air permeability, thermal conductivity, thermal diffusivity, thermal absorptivity, water vapour permeability and water vapour resistance. This study aimed to analyze thermal comfort properties of two kinds of outer shell, moisture barrier and thermal barrier fabrics and multi-layered combinations of them used in firefighter clothings. Two types of firefighter uniforms were also evaluated using thermal camera and analyses were conducted to show the thermal distributions under the same environmental and physical conditions.

Important findings can be derived from the thermal comfort test results by comparing single layer fabrics with their multi-layered combinations. Especially moisture barrier and thermal barrier fabrics have an important role on the multi-layered fabric structure's thermal conductivity and thermal resistance values. PU membrane with knitted fabric and Aramid felt quilted to Aramid/Viscose FR fabrics had lower thermal diffusivity and thermal resistance values and this leaded to lower thermal diffusion and thermal resistance characteristics in A1B1C1 structure (Nomex outer shell, PU membrane laminated to FR Knitted fabric moisture barrier and aramid felt quilted to aramid/viscose FR fabric thermal barrier). Thermal absorptivity gives the warm-cool feeling of fabrics and thermal absorptivity was found higher for A1B1C1 structure.

It was found that the overall moisture distribution in multi-layered fabric combinations is mainly influenced by using specific combinations of outer shell, moisture barrier and thermal barrier fabrics. As it was concluded by Keiser et.al.[27] moisture content of clothing structure is depend on the fabric layer combinations because moisture is transferred to the more hydrophilic fabric layer. In this study it was found that first and second layers in firefighter clothings proved to have high importance in water permeability and water vapour resistance values of multi-layered fabric combinations. Fabric types, A2 (PBI/Para-Aramid) and B2 (PU membrane laminated to FR Nonwoven Fabric) had lower water vapour resistance values than A1(Nomex) and B1(PU membrane laminated to FR Knitted Fabric) and this leaded to a lower resistance value for the three layered fabric structure of A2B2C2. Moreover relative water permeability was higher for A2B2C2 because of A2 and B2 fabrics.

Statistical analysis were also conducted to find relationships for thermal conductivity, thermal absorptivity, thermal diffusivity, water vapour resistance and water vapour permeability results and it was found high correlation values. As a result of thermal comfort tests and thermal camera evaluations, it was found that type 2 firefighter clothing (A2B2C2) had less temperature increase than the type 1 clothing (A1B1C1) because of its better water permeability,moisture permeability, thermal diffusion and absorptivity properties. In the literature considering the case of firefighting, mostly Nomex and PBI fabrics were studied and compared. Nomex flame-resistant meta-aramid material was found to exhibit good flame resistance and good thermal comfort properties. Moreover, Polybenzimidazole (PBI) fibers offer improved flame resistance and retain its strength and flexibility after exposure to flame. In some studies, it was found that PBI fiber enhances good performance properties combining flame-resistance, thermal protection and comfort with its good moisture absorption property [28,29]. In this study, even though the fabric layer's mass per unit area are very close to each other, their thicknesses and material properties are different from each other. Thus, differences in different fabric layers resulted different thermal comfort performances.

This study compared two firefighter uniforms (PBI and Nomex outer shell) that were mostly used types in fire situations. Since different structural properties of the fabric samples and firefighter clothings were used in the experiments, the results are only valid for these particular conditions. As a future study, it is aimed to study with Nomex and PBI fibers as the outer shell and combine them with different types of moisture barrier and thermal barrier fabrics. Then, the effects of different fabric combinations on the thermal comfort properties of firefighter uniforms will be considered and analyzed.

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