Thermal comfort properties of firefighters’ clothing with underwear

S H Eryuruk1, V Koncar2, F Kalaoglu1, H Gidik3 and X Tao2
1Istanbul Technical University, Textile Technologies and Design Faculty, Textile Engineering Department, 34437, Istanbul, Turkey
2ENSAIT, Ecole Nationale Supérieure des Arts et Industries Textiles, 59056, Roubaix Cedex 1, France
3UCLille, HEI, GEMTEX, F-59046 Lille, France
eryuruk@itu.edu.tr

Abstract. Optimal comfort will enable the wearer to work efficiently over long periods of time and help to protect the body from imminent overheating. The thermal performance of firefighters’ protective clothing is primarily based on the thermophysical properties of the materials that are used to construct the clothing. In this study, we have used new fire resistant underwear. The main purpose of this study is to evaluate the single fabric layer thermal comfort behaviours of underwear, outer shell, moisture barrier and thermal barrier fabrics together with their three-layered and four-layered combinations to understand their multilayer fabric thermal comfort performances.

1. Introduction
Protection together with comfort is a very important subject for firefighters’ performance and health. Heat and moisture transfer from the skin through the multilayer textile structures has a direct influence on the performance and safety of the firefighters. Thermal protective garments and firefighters uniforms are produced using special multilayered fabrics which are bulky and heavy. Thermal protection from fire and metabolic heat stress generated by the human body due to metabolic activities must be balanced [1-7].

Chung and Lee studied comfort of protective clothing for fire fighters and suggested on choosing system of clothing designs and material layers to balance protection and comfort [8]. Mah and Song outlined factors affecting firefighting clothing’s heat and moisture transfer capacity material properties, the style, fit, size and drape of garments [9]. Li et al. research work evaluated the effects of material components and design features on heat transfer properties of firefighter turnout clothings [10]. By using a sweating manikin, heat and moisture transfer performances of firefighter turnout clothings including outer shell, moisture barrier and thermal liner were evaluated considering clothing material, design, size, accessories (design details in clothing) and clothing design. Lawson and Vettori suggested that thermal performance of firefighters clothings must be evaluated while dry, when wet, in full loft and when fully compressed [11]. Wanga et al. concluded that the thermal and moisture comfort of firefighters’ ensembles when combined with the polyester inner clothing was worse than the other types of inner clothing [12]. He et. al. studied heat and moisture transfer in a multilayer protective fabric system under various ambient conditions [13].

The firefighter garments typically consist of three single layers of technical fabrics; outer shell fabric, moisture barrier fabric and thermal barrier fabric. Besides firefighter uniforms, firefighters also
wear underwear garments inside their clothings. In this study, we have used new fire resistant underwear. The main purpose of this study was to evaluate thermal comfort behaviours of the single fabric layers, outer shell, moisture barrier and thermal barrier fabrics together with their three-layered and four-layered combinations to understand their multilayer fabric thermal comfort performances. One firefighter garment type was selected for the study.

2. Materials and Methods

Fabric properties are presented in Table 1.

| Fabric Code  | Fabric Type                                                                 | Mass per unit area (g/m²) |
|--------------|-----------------------------------------------------------------------------|---------------------------|
| Outer Shell  | 75% Meta Aramid-23% Paraaramid-2% Antistatic                                | 200                       |
| Moisture Barrier | 85% Metaaramid-15% Paraaramid  
PU membrane laminated to FR nonwoven Fabric | 120                       |
| Thermal Barrier | Aramid felt quilted to Aramid/Viscose FR nonwoven fabric                    | 115                       |
| Underwear   | 78% FR Viscose, 20% Paraaramid, 2% Antistatic                              | 220                       |

Thermal comfort properties of the firefighter clothing and underwear were evaluated considering three comfort properties, thermal resistance, water vapour permeability and moisture management properties of fabrics. The sweating guarded hot plate apparatus was used to measure the thermal resistance of clothings (Rₐₜ) (m²K/W), under steady-state conditions according to ISO 11092 (ISO, 1993) [14]. The temperature of the guarded hot plate was kept at 35°C (like human skin) and for the determination of Rₐₜ of the fabrics, the standard atmospheric conditions were set as 65% R.H and 20°C. Water vapour permeability is the ability of a material to allow water vapour to pass through it. Water vapor permeability values of the samples were measured using the dish method, according to ISO 15496 (ISO, 2004) standard [15]. This method involves determination of weight losses with the evaporation time (24 h) of water contained in a cup, the top of which is covered by the cover ring. The difference in water loss between a cup covered with the reference fabric and one with the test fabric enables to study the relative rates of moisture movement through the test fabrics, so that the moisture vapor permeability of the test specimen can be calculated. Moisture management tester (MMT) was used to evaluate moisture management properties [16]. This method quantitatively measured the liquid moisture transfer in one step in a fabric in multi directions, where liquid moisture spreads on both surfaces of the fabric and transfers from one surface to the opposite.
3. Results

3.1. Thermal Resistance Results
Thermal resistance represents thermal insulation property of a fabric, the higher the thermal resistance, the higher the thermal insulation capacity of a fabric. As the number of fabric layers increased, thermal resistance of fabrics increased (Figure 4). Also it was found high $R^2$ values between thermal resistance & fabric thickness (0.978) and thermal resistance & fabric weight (0.724) (Figure 5 and Figure 6).

![Figure 4. Thermal resistance results](image)

![Figure 5. Thermal resistance & thickness linear regression graph](image)

![Figure 6. Thermal resistance & weight linear regression graph](image)

3.2. Water Vapour Permeability Results
Water vapour permeability is the ability to transmit vapour from the body. Water vapour permeability and water vapour permeability index of fabrics are seen in Figure 7 and 8. As it is seen from the figures, underwear and outer shell fabrics had the highest water vapour permeability values. As the number of fabric layers increased, the water vapour permeability of fabrics decreased and this means that the uncomfortable sensation increases. Moreover it was found a negative correlation between water vapour permeability and water vapour permeability index and fabric thickness (Figure 9 and Figure 10).
moisture management capacity (OMMC) is an index to indicate the overall ability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance: moisture absorption rate of the bottom side, one-way liquid transport ability, and moisture drying speed of the bottom side, which is represented by the maximum spreading speed. Overall moisture management capacity (OMMC) is an index to indicate the overall ability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance: moisture absorption rate of the bottom side, one-way liquid transport ability, and moisture drying speed of the bottom side, which is represented by the maximum spreading speed.

3.3. MMT Results
Liquid moisture transfer in clothing significantly influences the wearer’s perception of moisture comfort sensations. Dynamic liquid transfer values of clothing materials were measured using MMT test instrument. Cumulative one-way transport capacity (OWTC) is the difference in the cumulative moisture content between the two surfaces of the fabric in the unit testing time period. Overall moisture management capacity (OMMC) is an index to indicate the overall ability of the fabric to manage the transport of liquid moisture, which includes three aspects of performance: moisture absorption rate of the bottom side, one-way liquid transport ability, and moisture drying speed of the bottom side, which is represented by the maximum spreading speed.

Table 2 shows cumulative one-way transport capacity (OWTC) and overall moisture management capacity (OMMC) obtained from the MMT test device. As it is seen underwear fabric and thermal liner fabric had the highest liquid moisture management capacities (OMMC) and one-way transfer capacities (OWTC), showing that liquid sweat can be transferred from next to the skin to the outer surface to keep the skin dry. Moisture management and outer shell fabrics face side had poor liquid moisture management properties and negative one-way transfer capacities (OWTC) indicating that the liquid (sweat) cannot diffuse easily from the next-to-skin surface to the opposite side and will accumulate on the top surface of the fabric. These fabrics were found as a water repellent fabrics according to MMT results. As the number of layers were increased, fabrics were getting more water proof. 3 layered and 4 layered fabric structures had zero OMMC values and very high and negative accumulative one-way transport index values. Back sides had lower one way transport index values which were nearly half of the front sides. According to the MMT results, these fabrics have been
found as waterproof fabrics. Underwear fabric had also a positive effect by increasing accumulative one way transport index on the back side.

Table 2. MMT Results of fabrics

| Fabric Code         | Accumulative one-way transport index (%) | OMMC  |
|---------------------|------------------------------------------|-------|
| Underwear front     | 97.168                                   | 0.447 |
| Underwear back      | 114.776                                  | 0.502 |
| Outer shell front   | -717.590                                 | 0.000 |
| Outer shell back    | -243.534                                 | 0.083 |
| Moisture barrier front | -981.595                               | 0.000 |
| Moisture barrier back | -997.663                              | 0.000 |
| Thermal liner front | 66.970                                   | 0.455 |
| Thermal liner back  | 453.438                                  | 0.757 |
| 3 layer front       | -1015.405                                | 0.000 |
| 3 layer back        | -568.148                                 | 0.000 |
| 4 layer front       | -1036.212                                | 0.000 |
| 4 layer back        | -417.720                                 | 0.000 |

4. Conclusions

In this study the single fabric layer’ (underwear, outer shell, moisture barrier and thermal barrier fabrics) thermal comfort behaviours were measured together with their three-layered and four-layered combinations. As a result of study, it was found that as the number of fabric layers increased, thermal comfort properties of firefighter clothing are getting worse. As the number of fabric layers increased, thermal resistance of fabrics increased and the water vapour permeability of fabrics decreased meaning that the uncomfortable sensation increases. MMT results showed that underwear fabric and thermal liner fabric had the highest liquid moisture management capacity (OMMC) and one-way transfer capacity (OWTC), showing that liquid sweat can be transferred from next to the skin to the outer surface to keep the skin dry. Moisture management and outer fabric face side had poor liquid moisture management properties that the liquid (sweat) cannot diffuse easily from the next-to-skin surface to the opposite side and will accumulate on the top surface of the fabric. As a general conclusion for MMT results is that, as the number of layers increased, fabrics were becoming more water proof. On the other hand, underwear fabric had a positive effect by increasing accumulative one way transport index from back to front side.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 644268.

References

[1] Teunissen L P J, Wang L C, Chou, S N 2014 Evaluation Of Two Cooling Systems Under a Firefighter Coverall Applied Ergonomics 45 6 pp 1433–1438
[2] Levels D, Koning K, Mol J J, Foster E, Hein C, Daanen A M 2014 The Effect Of Pre-Warming On Performance During Simulated Firefighting Exercise Applied Ergonomics 45 6 pp 1504–1509
[3] Chung G S, Lee D H 2005 A Study On Comfort Of Protective Clothing For Firefighters Elsevier Ergonomics Book Series 3 pp 375-378
[4] Jiang Y Y, Yanai E, Nishimura K, Zhang H, Abe N, Shinohara M, Wakatsuki K, 2010 An Integrated Numerical Simulator For Thermal Performance Assessments Of Firefighters’ Protective Clothing Fire Safety Journal 45 pp 314-326

[5] Kim J H, Williams W J, Coca A, Yokota M, 2013 Application Of Thermoregulatory Modeling To Predict Core And Skin Temperatures In Firefighters International Journal of Industrial Ergonomics 43 1 pp 115-120

[6] Eryuruk S H 2016 Analysis of Thermal Properties of Firefighter’s Protective Clotthings Tekstil ve Konfeksiyon 26 3 pp 270-279

[7] Gidik H, Bedek G, Dupont D, Codau C, 2015 Impact Of The Textile Substrate On The Heat Transfer Of A Textile Heat Flux Sensor Sensors and Actuators A: Physical A230 pp 25-32

[8] Chung G-S and Lee D H, 2005 A study on comfort of protective clothing for firefighters Environmental Ergonomics 3 pp 375-378

[9] Mah T. and Song G. W, 2010 Investigation of the contribution of garment design to thermal protection. Part 2: Instrumented female mannequin flash-fire evaluation system Textile Research Journal 80 14 pp 1473–1487

[10] Li J, Barker R L and Deaton A S, 2007 Evaluating the Effects of Material Component and Design Feature on Heat Transfer in Firefighter Turnout Clothing by a Sweating Manikin Textile Research Journal 77 2 pp 59-66

[11] Lawson R and Vettori R L, 2002 Thermal Measurements For Fire Fighters Protective Clothing. Building and Fire Research Laboratory National Institute of Standards and Technology (NIST) Gaithersburg MD 20899 pp 1-15

[12] Wanga Y, Zhang Z, Li J and Zhua G, 2013 Effects of inner and outer clothing combinations on firefighter ensembles’ thermal- and moisture-related comfort levels The Journal of The Textile Institute 104 5 pp 530–540

[13] He J, Li J and Kim E, 2015 Assessment of the heat and moisture transfer in a multilayer protective fabric system under various ambient conditions Textile Research Journal 85 3 pp 227-237

[14] ISO 11092 Textiles-physiological effects-measurements of thermal and water-vapour resistance under steady-state conditions (sweating guarded hotplatetest) (ISO, 1993), Genève

[15] ISO 15496 Textiles – measurement of water vapour permeability of textiles forthe purpose of quality control (ISO, 2004), Genève

[16] Li Y, Xu W and Yeung K W, Moisture Management of Textiles U.S. patent 6,499,338 B2 2000