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A Smart Jacket Design for Firefighters

İtfaiyeciler için Akıllı Bir Ceket Tasarımı

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A SMART JACKET DESIGN FOR FIREFIGHTERS

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ABSTRACT: A firefighter protective clothing consists often of three-layered fabric structure; an outer shell, a moisture barrier and a thermal liner. In this study, an innovative firefighter protective jacket is proposed, designed to protect firefighters within the thermal environment. The protective performances of different three-layered fabrics were initially tested, and the most appropriate fabric combination for firefighter protective clothing was determined. After the fabric selection process, a firefighter jacket was designed and produced by using the most appropriate fabric combination. A specially designed electronic system equipped with related sensors was integrated to the jacket. Finally, the designed firefighter jacket with integrated sensors was tested in a heating oven.

Keywords: Firefighter protective clothing, smart garment, MCDM, TOPSIS.

İTFAİYECİLER İÇİN AKILLI BİR CEKET TASARIMI

ÖZET: İtfaiyeci koruyucu giysisi, genellikle koruyucu bir dış katman, nem bariyeri ve termal astarı içeren üç katmanlı kumaş yapısından oluşmaktadır. Bu çalışmada, termal ortamdaki itfaiyecileri korumak amacıyla tasarlanmış yenilikçi bir itfaiyeci koruyucu ceketi önerilmiştir. İlk olarak farklı üç katman kumaşların koruma performansları test edilmiş ve itfaiyeci koruyucu giysisi için en uygun kumaş kombinasyonu belirlenmiştir. Kumaş seçiminden sonra, en uygun kumaş kombinasyonu kullanılarak bir itfaiyeci ceketi tasarlanmış ve üretilmiştir. İlgili sensörlerle donatılmış özel olarak tasarlanmış bir elektronik sistem cekete entegre edilmiştir. Son olarak; entegre sensörlerle tasarlanmış itfaiyeci ceketi, ısıtılan bir etüv içerisinde test edilmiştir.

Anahtar Kelimeler: İtfaiyeci koruyucu giysi, akıllı giysi, MCDM, TOPSIS.

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1. INTRODUCTION

The duty of a firefighter is to extinguish fire, manage emergency situations and help to minimize human and material losses [1]. Therefore, the firefighter protection from clothing is equally as important as intensive firefighting training [2]. Firefighter protective clothing is thermal protective clothing, which protects against thermal radiation, hot gas convection, and heat conducted from hot surfaces [3]. It usually consists of three main layers: an outer shell, a moisture barrier and a thermal liner [4]. The selection of the best possible fabric combination is the key step in firefighter protective clothing design. As there are many different criteria for such a selection problem, due to different requirements, the problem can be formulated as a multiple criteria decision making (MCDM) problem. In order to meet the desired cost constraint and performance enhancement criteria, many material alternatives must be carefully evaluated.

Firefighters are the occupational group most frequently exposed to hot thermal environments [5, 6, 7]. Heat stress is a significant factor for firefighters, and one of the primary safety challenges. When firefighters are exposed to high temperatures for a substantial time interval, although their protective clothing may exhibit no visible thermal damage, the internal temperature may rise to a critical point at which the heat losses through sweat evaporation that cool the firefighter can no longer be maintained. The heat from outside environment causes the temperature of the epidermis to exceed above 44 ºC, and skin burns occur. The evaporation of sweat causes a cooling effect, which may mislead the firefighters about the level of danger. Then, firefighters may enter a dangerous thermal environment with higher temperatures without realizing the possible skin burning hazard. This danger is not usually realized until the last moment before the protective clothing dries out. When this occurs, the protective clothing temperature may rise suddenly, and serious burn injuries occur [3]. To prevent this, it is highly important to monitor the internal and ambient temperature of the firefighter.

In recent years, researchers from textile and electronic science have conducted many interdisciplinary studies to measure physiological parameters (temperature, humidity, heart rate, carbon dioxide, etc.), using sensors and electronic control systems integrated into the garment. These smart garments monitor the body and environmental signals to prevent dangerous situations.

Kremens et al. integrated a small lightweight, portable device into a firefighter's jacket, which can record and report the health, location and status parameters of the firefighter [8]. The Viking Company designed and produced a smart firefighter coat to reduce risks of heat stress and burn injuries. In their design, thermal sensors were attached to the arm and the shoulder of the coat to monitor the temperature inside and outside the coat [9]. Another smart coat application is an alarm that triggers when the external temperature reaches the set limit value. In this design, six silicone-encapsulated heat sensors were placed on the chest, back and arm parts of the coat. The controller evaluates the internal temperature signal every ten seconds until one or more sensor reaches 37.8 °C, after which the controller monitors every sensor every second. When the internal temperature of the coat approaches 65.6 °C, the alarm system is triggered [10]. Hertleer et al. designed a textile antenna on an aramid fabric for integration in a firefighter outer garment to transmit the firefighter's vital signals to a nearby base station. For this purpose, a multilayer micro strip patch antenna was located underneath the moisture barrier, and the thermal barrier layer in the area of shoulders or the upper arm. The selected placement area of the antenna is effective to reducing the risk of creasing and wrinkling [11]. In the framework of ProeTEX, to prevent heat stroke, Oliveira et al. monitored thermal parameters of firefighter, including internal temperature, environmental temperature, and heat flux [12]. Smart@fire is a project to support companies and researchers and provide them with financial means to develop Innovative ICT Solutions to improve firefighter protecttion and to integrate a solution into smart personal protective equipment (PPE). The ultimate goal is to develop cost-effective and functional PPE for a broad market [13].

This study is the result of a project done to protect the health of the firefighter and minimize possible thermal hazards. For this purpose, a fabric combination selection problem for firefighter protective jacket was performed by Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a well-developed Multiple Criteria Decision Making (MCDM) technique. Then, a basic cost/benefit analyses based on TOPSIS results was performed. A design for firefighter jacket was produced by using determined three-layered fabric combination. Moreover, a specially developed electronic system and software were integrated into the jacket to monitor the internal temperature, ambient temperature, and the position of the firefighter.

2. MATERIALS AND METHODS

2.1. Three-layered fabrics and firefighter protective clothing

Firefighters may receive serious burn injuries even when using conventional protective clothing, due to definite physical limits in its ability to protect the wearer. It may be a challenge to meet all requirements for the conventional firefighter protective clothing. Therefore, in the present study, various outer shell, moisture barrier and thermal liner fabrics were combined to obtain fourteen different three-layered fabric combinations. The combination of three fabrics which provide optimum protection and cost was determined by applying the TOPSIS method, combined with a cost/benefit analysis. The mass per unit area and the thickness of the combinations were measured. The performance of the combinations against flame and water vapor resistance were tested according to the standards TS EN 367 [14] and TS EN 31092 [15], respectively. The performance of the combinations against flame was measured by using the test equipment heat transfer-flame. The water vapor resistance was measured by using the sweating guarded hotplate. These two measurements and two test results were used as the decision criteria because these parameters are key elements in the protection and comfort in the firefighter jacket. The CRiteria Importance Through Inter-criteria Correlation (CRITIC) method was used to assign a weight value for each criterion in respect to test results and measurements. Then, TOPSIS method was used to evaluate alternatives in terms of benefits, and finally a simple cost/benefit analysis (CBA) was applied to rank the fabric combination alternatives. Finally, a new firefighter jacket was designed using the fabric combinations selected according to the TOPSIS method and CBA.

CRITIC is an objective weighting method. Objective methods obtain the weights based only on the known data for a problem and are useful in the absence of a decision maker [16, 17]. TOPSIS is a reliable method for solving multi-criteria decision making problems and providing the optimal solution or the ranking of alternatives [18, 19]. TOPSIS has been successfully applied to many diverse decision making problems [18- 21]. In the literature, no study has attempted to solve the protective fabric selection problem by the use of MCDM. CBA consists of a set of procedures for defining and comparing benefits and costs.

2.2. Electronic System and Equipment

An electronic system consisting of a main unit, sensors, and warning systems was designed, built and integrated into the produced firefighter jacket. The main unit consists of a 7.4V lithium polymer (Li-Po) battery, 3.3V voltage regulator, 7.4V LED driving logic circuit, a microcontroller, and a sound module. The input signals to the main unit are provided by the internal temperature sensor, humidity sensor, ambient temperature sensor, and force-sensing sensors. The outputs of the main unit are a mono earphone for audio warnings and a LED strip for visual warnings. An accelerometer, integrated into the main unit, detects the status of the firefighter; i.e. whether lying down or standing. Figure 1 shows the blockdiagram of the electronic control unit that consists of the main board, sensors and warning systems.

A Li-Po battery charge dock was designed using the same 26 pin connector structure used in the firefighter jacket to provide connection compatibility. At the beginning of any mission, the firefighter simply removes the unit from the charge dock and connects it to the firefighter jacket input connector to activate the system automatically, without the need to switch on. After the mission, the control unit is removed from the jacket connector and replaces on the charge dock. Two batteries in the electronic control unit are charged with a Li-Po battery charge dock unit, which contains two separate chargers for safe and balanced charging.

The microcontroller is an 8-bit ATMEGA 328P. Audio unit is the SOMO-14D sound module, which plays pre-recorded AD4 formatted sound files. The internal temperature sensor is DALLAS DS18B20. The ambient temperature sensor is PT1000 type Resistive Temperature Detector (RTD) sensor. The humidity sensor is small-sized HIH- 4030 sensor. The force- sensitive button is a resistor (FSR) that is a square type 0.1 – 10 kg/cm² range force sensitive sensor. The accelerometer is Hitachi H48C 3-Axis accelerometer module. The earphone is 32 Ω and 20 kHz mono type speaker. The LED strip is flexible and silicone coated.

A heating oven combined with a personal computer was used to test and confirm the accuracy of the sensors. An Arduino program was developed to read the sensor data, and to send it to a personal computer via a serial communication channel. The personal computer was equipped with a MATLAB program developed to record the received sensor data into excel or text file, which can be used in the graphical analysis.

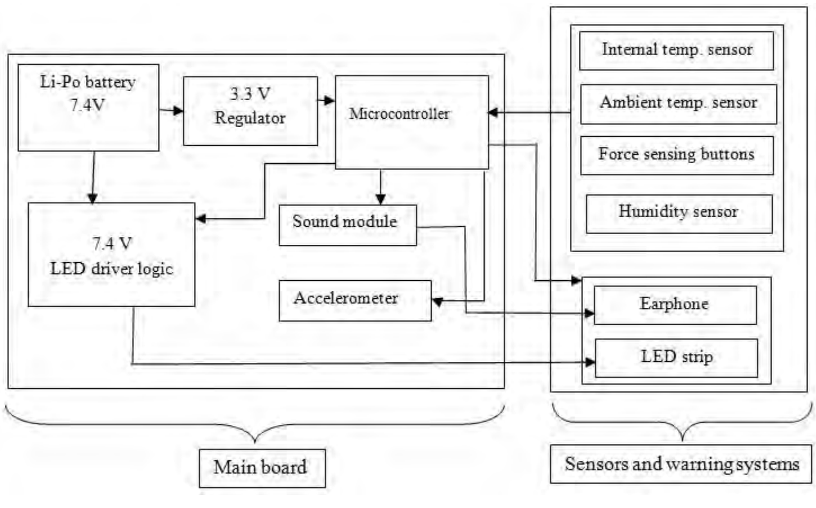

Figure 1 Blockdiagram of electronic system

3. RESULTS

3.1. Selection of three-layered fabrics for firefighter's jacket

The first step in the design of firefighter protective clothing is to select conventional materials for three layers, which are an outer shell, a moisture barrier, and a thermal liner. This selection case can be formulated as a multiple criteria decision making (MCDM) problem. There are many different selection criteria, due to the complex requirements of the firefighter protective clothing. These include low mass per unit area, low thickness, low water vapor resistance and high performance against heat and flame. In this study, all these features are defined as selection criteria.

The first step was to create a decision matrix, which has fourteen fabric combinations as alternatives on the rows and four criteria on the columns. The results of the laboratory tests and measurements were conducted to determine the criteria values for each alternative and used to obtain a decision matrix. The created decision matrix is shown in Table 1.
First of all the values in decision matrix were used in CRITIC approach to determine the order of importance of the four criteria. All values in the decision matrix were normalized and CRITIC approach was applied to ensure the objective weightings of the criteria. According to the weights of CRITIC method, the most important criteria was the performance level for TS EN 367 - Heat Transfer Flame. The other criteria were ranked in descending order as follows: thickness, mass per unit area and water vapor resistance. These criteria weights were used in TOPSIS method. Then, the alternatives were ranked according to the relative closeness to the ideal solution in TOPSIS method. The closeness values were normalized, and used for the benefit values in CBA. The ranking of the alternatives and the corresponding normalized values obtained from the TOPSIS method are presented in Table 2.

Table 2 Ranking of alternatives according to the TOPSIS method

Ranking of Alternatives	Normalized values obtained from TOPSIS (Weights of Benefits)
C10	0,1344
C8	0,1123
C9	0,0991
C3	0,0991
C1	0,0931
C2	0,0836
C7	0,0642
C6	0,064
C13	0,0509
C12	0,0462
C14	0,0402
C11	0,0393
C4	0,0373
C5	0,0362

The higher the closeness values from TOPSIS method, the higher the ranking of the samples. When it is considered that the performance level against heat and flame, the most important criteria is the tenth combination is the optimal fabric combination.

The cost of fabric combinations for firefighter protective clothing differs depending on the fabric type used for each of the three layers. Since there are several types for each layer, cost calculations were made by considering the various types of fabrics.

The costs of fabric combinations were normalized in order to perform the Cost/Benefit Analysis. The determined weights of costs are presented in Table 3. As seen, the most costly combination is the tenth alternative, C10.

Table 1 Decision matrix for selection of the three-layered fabric combinations

ALTERNATIVES (COMBINATIONS)	CRITERIA			
	Mass per Unit Area (g/m^2)	Thickness (mm)	Performance Level (TS EN 367) (s)	Water Vapor Resistance (TS EN 31092) (m² Pa/W)
C1	556,900	5,300	16,004	26,810
C2	596,750	5,432	14,999	27,310
C3	647,750	6,266	16,233	30,540
C4	545,200	3,542	10,626	21,310
C5	528,650	3,069	11,290	21,700
C6	587,950	3,580	14,497	19,460
C7	571,400	3,635	14,420	19,520
C8	585,200	5,010	18,617	26,020
C9	625,050	4,393	18,322	26,950
C10	676,050	6,679	20,216	25,400
C11	573,500	2,860	12,362	21,430
C12	556,950	2,969	13,163	21,470
C13	616,250	2,939	14,022	21,800
C14	599,700	3,040	12,976	23,290

Table 3 Ranking of alternatives according to the weights of costs

Ranking of Alternatives	Weights of Costs
C10	0,0982
C13	0,0890
C11	0,0871
C9	0,0815
C8	0,0797
C3	0,0769
C14	0,0705
C12	0,0686
C6	0,0677
C4	0,0658
C2	0,0602
C1	0,0584
C7	0,0491
C5	0,0473

After the calculating weights of benefits (Table 2) and cost weights of each alternative (Table 3), the cost/benefit analysis was used to determine to the final ranking of alternatives. The obtained benefit/cost ratios are presented in Table 4.

Table 4 Benefit/Cost ratios

Ranking of Alternatives	Benefit/Cost Ratios
C1	1,594
C8	1,409
C2	1,390
C10	1,368
C7	1,307
C3	1,289
C9	1,216
C6	0,946
C5	0,766
C12	0,673
C13	0,572
C14	0,571
C4	0,567
C11	0,451

The first combination, C1 is the most appropriate alternative when the cost and the benefit performance were taken into account. The tenth combination, C10, with the best performance in respect to benefit values, is in back rows for cost/benefit ratios, and therefore was not selected. The ranking of the other alternatives can also be observed and compared in terms of benefits and costs in Table 2, 3 and 4. The best fabric combination, together with details of each layer is given in Table 5 [22].

3.2. Design of firefighter protective jacket

Following the selection of the optimal fabric combination, the firefighter jacket was designed and produced by taking into consideration the ergonomics, ease of maintenance and protection level. The jacket prototype was produced in 149 operations using lockstitch machine, overlock machine, double needle sewing machine, fabric reversing machine, velcro machine, band machine and snaps machine operations. The outer shell was designed to allow separation from the other two layers, which are stitched together. The outer shell is attached to these two layers with velcro tape. An illustration of the firefighter jacket is seen in Figure 2.

Figure 2 The drawing of the firefighter jacket

Two bellows pockets were sewn into either side of the jacket. A hidden pocket, containing sensors and warning systems is located over the bellows pocket on the right. Another pocket is located behind the right bellows pocket to hold the main unit. The outer shell fabric is separated from the other layers with velcro tape. The hidden pocket and the pocket of the main unit can be seen underneath the outer shell in Figure 3.

Table 5 The three layers of the selected fabric combination C1.

COMBIN.	OUTER SHELL	MOISTURE BARRIER	THERMAL LINER
C1	165 g/m^2 PBI Triguard [22]	90 g /m^2 FR Nonwoven (Meta-aramid+Para-aramid+Melamine)	130 g/m^2 50**%** Nomex-50**%** Viscose FR woven fabric + 130 g/m^2 regenerated felt, needle punch.

Figure 3 The hidden pocket and the pocket of the main unit

3.3. Electronic system design

In this study, an electronic system, consisting of sensors was created to monitor the internal temperature, the ambient temperature, the humidity of the environment, the position of the firefighter and the state of force sensing buttons. The sensor values are compared with the defined critical threshold values, and the wearer is accordingly warned with sound and LED blink warnings. The sound warnings, delivered by earphone, are audio messages which are pre-recorded by a human speaker. LED warnings are clearly visible through a change in blinking frequency. The firefighter can adjust the sound volume according to need by touching the force sensing buttons. The position of the firefighter, i.e. lying or standing, is detected by an accelerometer in the main unit. The designed electronic circuit with the sensors, warning systems (LED strip and earphone), main unit box and the ribbon cable are seen in Figure 4.

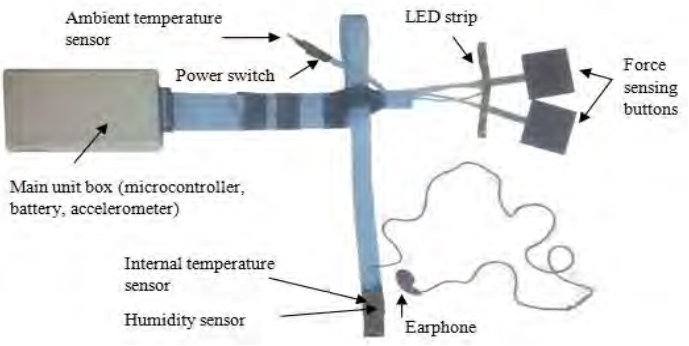

Figure 4 The electronic circuit

All components were selected to create a compact and lightweight electronic system. The electronic control system is located on a printed circuit board inserted into a water- and heat-resistant plastic box. High heat resistant ribbon cables provide an electrical connection between the box, sensors and warning systems.

3.4. Integration of the electronic system to the firefighter jacket

The electronic equipment is located under the outer shell fabric in the right side of the jacket. The outer shell protects sensors from heat, water and tearing. Two force sensing buttons are located under the outer shell in the hidden pocket. For visible the LED strip can be removed from the hidden pocket through a small buttonhole, when needed. The ambient temperature sensor is directed towards the outer face of the jacket from an eyelet to measure the external temperature. A humidity sensor, an internal temperature sensor, and a power switch are integrated into the surface of the inner liner on the right side of the jacket. The internal temperature sensor and the humidity sensor measure the values inside the jacket. The earphone connection extends from this area and passes through the velcro tape between the outer shell and the other layers. Behind the bellows pocket and under the hidden pocket, there is another pocket which holds the main unit box. The electronic equipment is connected with the heat-resistant ribbon cables. In Figure 5, the location of the electronic system is seen on the right side of the jacket.

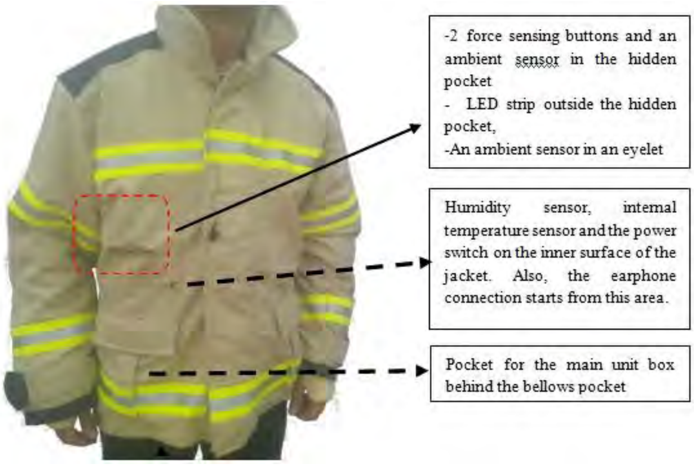

Figure 5 The placement of the electronic system

The hidden pocket entry is on the rear surface of the outer shell. The sensors, the warning systems in the hidden pocket, and the main unit in bellows pocket is connected with ribbon cables under the outer shell. The LED strip is coated with silicon, and therefore, heat resistant. The hidden pocket is shown in Figure 6.

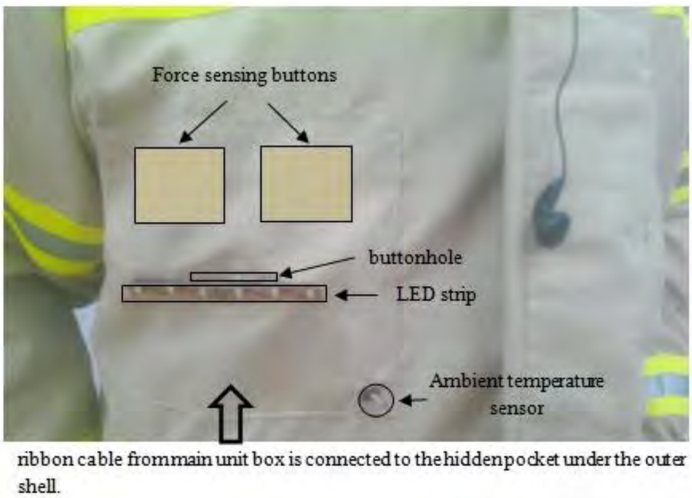

Figure 6 Electronic equipment in hidden pockets

The electronic circuit can be removed from the jacket when the jacket needs to be washed, or when the batteries in the main unit need replacing. The main unit box can be removed from the system, and can be connected to the charge unit.

The electronic control unit software was developed to collect accurate data from all the sensors and to operate the warning systems based on sensor data processing. The collected sensor data were also transferred to a personal computer using serial communication. The conditions for activity the alarm were determined by observing the trend graphics of the collected sensor data and considering the important temperature values in the literature [3]. The software was designed to determine the warning outputs, according to the sensor threshold values.

LEDs are controlled by the collection and evaluation of internal temperature and ambient temperature sensor values. In normal light conditions LEDs are turned off to save the battery life. When the internal temperature sensor records the temperature values over 44 °C, warning LEDs flash ten times per second. When the ambient temperature sensor measures the temperature value over 200 °C, LED’s blink five times per second.

Three different warnings through the earphone are as follows:

- When the internal temperature exceeds the value of 44 °C, the warning is 'Internal Temperature is Critical'.
- When the ambient temperature exceeds the value of 200 °C, the warning is 'Environmental Temperature is Critical'.
- When the firefighter is at the lying position, the warning is “You are not standing” in order to recover consciousness.

3.5. Testing of the firefighter protective jacket at high temperature

The temperature sensors and humidity sensors were tested in a heating oven to test the accuracy of their operations. The measurements values of the sensors were monitored and evaluated at increasing and decreasing ambient temperatures. The test was repeated three times. The measurement results are the test results repeated three times.

Firstly, the developed electronic circuit was integrated into the firefighter jacket. Then the integrated prototype jacket was placed in the oven. The jacket was exposed to increased heat, continuous measurements were taken from the internal temperature sensor, ambient temperature sensor and humidity sensor inside the jacket. The collected sensor data were saved on a computer using the MATLAB program.

The oven was set to 200 °C. The temperature of the oven heated up to 200°C in about 25 min, then the oven temperature was kept stable for 3 minutes, and finally the oven was switched off. After about 2 minutes, the oven door was opened to allow the ambient temperature to reduce. In this process, the electronic circuit operated and the sensor data were recorded continuously. The oven test took in approximately 70 minutes. During the test, no problems were observed with the sensor or the battery operations.

Figure 7 shows the time-dependent change of the collected values of the internal temperature and the ambient temperature sensor.

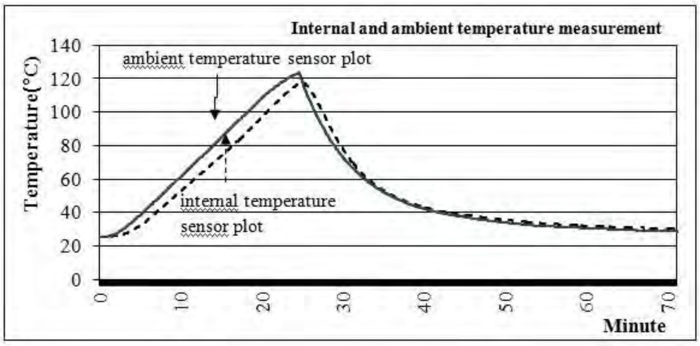

Figure 7. Time-dependent change graph of values collected from internal temperature and ambient temperature sensors

As shown in the graph in Figure 7, the maximum reached temperature level detected by the ambient temperature sensor is approximately 120 °C. The internal and the ambient temperature sensor plots show great similarity, but the ambient temperature rises faster than the internal temperature because the heating starts from the outside of the jacket.

Data was also collected from the humidity sensor during the test. The graph of the relative humidity values detected by the humidity sensor is shown in Figure 8.

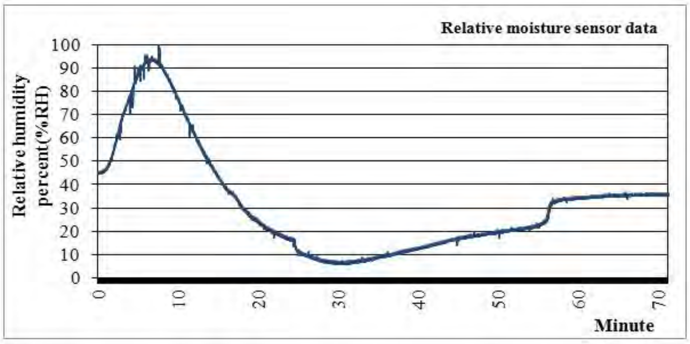

Figure 8. The graph of the relative humidity variation according to time

At the beginning of the test, the relative humidity is 45% in the oven environment. As the oven temperature increased, the relative humidity increased for a short time before the drying occurred, and the relative humidity decreased.

Lastly, the oven was turned off and the temperature started to fall. 5 minutes later, the relative humidity began to increase. Relative humidity decreased below the initial value and reached approximately 35% relative humidity at the end of the test.

In the oven test, since the sensors are protected by fabrics and not kept in the oven for a long time, they have not reached to the oven temperature. During the test, it has been observed that the sensors and the main unit are working correctly. As another test an external heat source exceeding the temperature of 200 degrees has been applied to the sensors. The operation of headphones and LEDs has also been tested and observed to be working correctly.

4. CONCLUSION

The performances and the price characteristics of the most commonly used fabrics in firefighter garments in our country were evaluated in this study. A smart and functional firefighter jacket was designed and produced, according to this evaluation and the needs of firefighters working in the fire department.

The most appropriate fabric assembly for the firefighter protective clothing was determined by using MCDM analysis along with a cost/benefit evaluation. This was the first time this method was used to determine the optimum three-layered fabric structure in firefighter protective garments.

An electronic circuit and software were developed, using temperature sensors, a humidity sensor, an accelerometer, force sensing buttons, and related visual and auditory warning systems. The designed system was integrated into the jacket with the latest sensor technologies and the electronic control units to create a smart jacket for firefighters. The design of the jacket includes ergonomics, ease of maintenance and good performance level.

The designed firefighter jacket was tested in a heating oven to confirm the functionality of the integrated electronic system. The measurement values of the temperature sensors were monitored and evaluated at increasing and decreasing ambient temperatures in the oven. It was observed that the main unit box, the high heat resistant cables, the sensors, and warning systems remained fully operational under the heating test condition.

This study introduces a new perspective into existing firefighter garment production, by developing a product using the latest sensor technology with a microcontroller system, a significant advance in terms of intelligent textiles. The new smart and functional firefighter jacket is the first intelligent and functional protective product developed based on cooperation between the textile and electronics sciences in Turkey in order to ensure the safety of firefighters.

In addition to the current research, more studies can be done as a future work, in particular, the designed smart firefighter jacket can be tested and evaluated in a fire simulation environment.

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