Analysis of the Thermal Comfort Properties and Heat Protection Performance of Cotton/Nylon-Kermel Fabrics

Ali Kakvan, Saeed Shaikhzadeh Najar, and Agnes Psikuta

***Abstract*—In this research, fire and radiant heat protection and thermal comfort properties of cotton/nylon-Kermel blended woven fabrics, were utilized to predict the thermal comfort and protection limit of this fabric structure based on Woo and Barker developed model. The results showed that the porosity, the air permeability and the thermal resistance increased with Kermel fiber blend ratio. Conversely, the water vapor resistance decreased with increase of Kermel fiber blend ratio up to 40%. The thermal conductivity of blended fabric didn't change with the increase in Kermel fiber blend ratio up to 40%. Cotton/nylon fabrics, particularly those containing 30% Kermel, exhibited the highest upper thermal comfort limit and also the widest range of fabric metabolic activity level. The Kermel fibers had a significant effect on prevention of fire diffusion and Radiant Protective Performance (RPP) of fabrics. The results of vertical wicking and MMT tests show that adding Kermel fibers up to 10% detracts these thermal comfort properties significantly. The results of this research suggest that blending Kermel fiber with cotton and nylon at a blend ratio of 30% enhances thermal comfort limit and heat protection of blended fabrics. Moreover, cotton/nylon (50/10) blended with 40% Kermel fiber leads to desirable thermal comfort properties.**

***Keywords*: kermel, thermal comfort limit, thermal conductivity, thermal resistance, radiant protective performance (RPP)**

I. INTRODUCTION

The desired heat protection has negative effects on the comfort and work efficiency of the wearer [1-3]. Hence, the major challenge in producing protective clothing is to keep a balance between protection and comfort for all types of protective clothing, depending on metabolic heat production and climatic conditions [3,4]. To evaluate the thermal comfort, a variety of thermal and moisture management properties such as fabric's thickness, weight, thermal insulation, resistance to evaporation, water repellence and air permeability must be determined [1,5]. Most types of protective clothing are uncomfortable to wear because they have not good heat and moisture transfer properties [6]. Also, it is necessary to find the relationship between the resultant comfort properties of protective clothing and the fiber characteristics (chemical composition, morphological characteristics, fineness, cross section, porosity and water content of fiber components), yarn and fabric structure, and finishing [7-17].

Clothing comfort includes two principal aspects: thermo-physiological and sensorial, which are combined to create a subjective perception of satisfactory comfort performance [7,8]. The former relates to the way the clothing dissipates metabolic heat and moisture, while the latter is related to the interaction of the clothing with the senses of the wearer. Therefore, heat and moisture transfer properties under both steady and transient conditions must be considered for prediction of wearer comfort, particularly with the tactile response of the skin [9-11].

Barker *et al.* have studied the thermal performance of protective fabrics and clothing systems [7,8,10,18-21]. They have found that the mechanism of heat transfer through the fabrics and the air gap comprises a complex combination of absorption and re-radiation, conduction and forced convection. Moisture raises the thermal insulation of single-layer protective fabric against high intensity radiant/convective heat exposures and against lower intensity purely radiant exposures, but it has an adverse effect on the thermal protective performance (TPP) of the same fabrics when tested in high intensity radiant exposure condition. Therefore, water absorbing protective fabrics can be expected to have higher TPP values if the TPP test involves direct contact with flames. The studies also indicate that the differences in fabric thickness and weight have a greater effect on the TPP of single layer protective fabrics than the difference in the fiber content.

There are several studies investigating the thermal performance of protective Kevlar and Nomex fabrics [7,8,10,18-21]. However, there has been no systematic study on thermal comfort properties of cotton/nylon fabrics blended with high performance protective Kermel fiber. Kermel fiber is a polyamide-imide, classified under the meta-aramid family. It is naturally non-flammable and maintains a maximal short term protection against high temperatures (up to 1000 °C). Kermel fibers do not melt nor burn when exposed to high temperatures [4,22,23]. The low modulus of the fiber is realized through the extreme softness of Kermel woven fabrics and knits. The smooth-surface and circular cross-section of fiber makes it comfortable [24]. It is well known that cotton as well as nylon fibers have good comfort properties [25].

Therefore, the main objective of this study is to combine the high comfort properties of cotton/nylon fibers with the high thermal performance of Kermel fibers to enhance the thermal comfort properties of woven fabrics. Accordingly,

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the thermal comfort properties of woven fabrics made from cotton/nylon fibers blended with Kermel fibers are investigated in this study. It is expected that the produced fabrics would have good potential to be used in safety clothes in metal, oil, gas and petrochemical industries and the military. We aim to investigate the thermal comfort limit and heat radiant protection performance of single layer cotton/nylon-Kermel woven fabrics for using in oil, gas and petrochemical industries and also in military protective clothing.

TABLE I
CHARACTERISTIC OF FIBERS

	Cotton	Nylon 66	Kermel
Length [mm]	32	40	50
Fineness [dtex]	1.46	1.7	1.7
Density [g/cm^3]	1.52	1.14	1.34
Thermal conductivity [mw/(m.K)]	71	250	40
Color	White	White	Green

TABLE II
PHYSICAL PROPERTIES OF COTTON/NYLON-KERMEL BLENDED FABRICS

Sample number	Blend	Thickness [mm]	Porosity [%]
1	50:50 Cotton/Nylon	0.63±0.01	72.86
2	50:40:10 Cotton/Nylon-Kermel	0.65±0.01	73.36
3	50:30:20 Cotton/Nylon-Kermel	0.64±0.01	74.15
4	50:20:30 Cotton/Nylon-Kermel	0.64±0.01	74.84
5	50:10:40 Cotton/Nylon-Kermel	0.64±0.01	76.18
6	100 Kermel	0.71±0.02	77.10

TABLE III
THERMAL COMFORT PROPERTIES OF COTTON/NYLON-KERMEL BLENDED FABRICS

Sample Number	Thermal Resistance [m^2 K/W×10^{-3}]	Thermal conductivity [W/K m]	Water vapor Resistance [m^2 Pa/W×10^{-3}]
1	16.68 ± 1.31	0.0555 ± 0.002	4.35 ± 0.38
2	17.92 ± 1.73	0.0585 ± 0.006	4.00 ± 0.33
3	20.25 ± 1.15	0.0588 ± 0.006	3.63 ± 0.08
4	19.72 ± 1.52	0.0588 ± 0.011	3.53 ± 0.26
5	22.28 ± 3.12	0.0573 ± 0.007	3.55 ± 0.16
6	29.78 ± 2.85	0.0498 ± 0.006	4.17 ± 0.37

II. FABRIC PREPARATION

The properties and characteristics of the fibers used in this study are shown in Table I. Kermel (100%), cotton/nylon (50:50) and four blends of 50% cotton fibers with nylon and Kermel (40:10, 30:20, 20:30 and 10:40) were ring spun and then twisted into two-folded yarns with the same yarn count of 30/2(Ne) and twist level of 560 TPM. In this study, six Ripstop woven fabrics were used for evaluation. All of the fabric samples had the same ends per centimeter of 26 cm^{-1}, picks per centimeter of 19 cm^{-1} and weight of 220 g/m^2. The fabrics were kept for 24h in standard ambient conditions for conditioning and relaxation. These fabric samples were only different in their fiber content. The thermal comfort and physical properties of the fabrics measured in our work are given in Tables II and III.

III. COMFORT LIMIT MODEL

We used a comfort limit for calculating the comfort properties of blended fabric samples. Woo and Barker [26] derived this comfort limit range by applying the First Law of Thermodynamics; the law of energy conservation:

$$\begin{aligned}&\text{Energy storage within body}(J) = \\ &\text{Energy Production}(Mn) - \text{Energy Dissipation}(G)\end{aligned} \tag{1}$$

If there is neither heat loss nor heat storage in the body, i.e. J=0, it leads to a comfort feeling. An equation for the energy dissipation from body into an ambient environment is as follows [27,28]:

$$\begin{aligned}&\text{Total energy dissipation}(Q) = \\ &\text{Dry heat transfer}(H) + \text{Evaporative heat transfer}(E)\end{aligned} \tag{2}$$

The heat balance equation is defined as follows:

$$Mn = Q = \left(\frac{1}{0.155I}\right)\left[(Ts - Ta) + 16.5 i_m (Ps - Pa)\right] \tag{3}$$

where Mn is the net metabolic rate (W/m^2), Q is the total energy dissipation (W/m^2), Ts and Ta are the temperatures of skin and ambient(°C) respectively, Ps is the saturated vapor pressure at skin temperature (kPa), Pa is the vapor pressure of ambient (kPa), I is the thermal resistance (clo), and i_m is the permeability index which is the ratio of thermal and evaporative resistance of the fabric divided by the ratio of thermal and evaporative resistance of air.

The limit of 20% sweat wetted area (SWA) has been suggested as the comfort limit [7,9,26]. By assuming Ts = 33 °C and Ps = 5.033 kPa, the comfort equation becomes [26]:

$$\left(\frac{6.46}{I}\right)(33 - Ta) \le Mn \le \left(\frac{6.46}{I}\right)\left[(33 - Ta) + 3.3 i_m (5.033 - Pa)\right] \tag{4}$$

This equation contains three groups of parameters that affect the comfort properties [26]: (1) the parameters that are a function of material type (I,i_m); (2) the parameters that are a function of environmental condition (Ta, Pa); and (3) a parameter that is a function of body activity (Mn). Our study has analyzed the effect of material type (Kermel fiber blend ratio) on the predicted level of comfort of cotton/nylon -Kermel blended woven fabrics.

IV. TESTING

The thicknesses of woven fabrics were measured using the Frank thickness tester (Karl Frank GmbH, Germany) at a pressure of 2kPa according to ISO 5084:1997. Fourteen tests were conducted for each fabric sample. The overall fabric porosity was determined by using (5) [17]:

$$Porosity(\Phi) = 1 - \frac{\rho_b}{\rho_s} \quad (5)$$

where ρ_b is the fabric density (g/cm^3) and ρ_s is the average fiber density (g/cm^3) calculated according to the percentage of blend ratio of the fibers in the produced yarns, as shown in (6):

$$\begin{aligned}&Average\ Fiber\ Density\ (\rho_s) = \\ &(p_1 \times \rho_1) + (p_2 \times \rho_2) + (p_3 \times \rho_3)\end{aligned} \quad (6)$$

where p_1, p_2, p_3 are the percentage and ρ_1, ρ_2, ρ_3 are the densities of cotton, nylon and Kermel fibers, respectively. Fabric density depends on the weight and thickness of fabric, as shown in (7):

$$\begin{aligned}&Fabric\ density\ (g/cm^3) \\ &= \frac{Fabric\,Weight\,(g/cm^2)}{Fabric\,Thickness\,(cm)}\end{aligned} \quad (7)$$

The following thermal comfort properties of fabrics were measured using the mentioned standard test methods:

- Thermal and water vapor resistance under steady-state conditions using sweating guarded-hotplate, according to ISO 11092
- Air permeability of fabrics using ELPA (Empa, Switzerland) according to ISO 9237:1996
- Thermal conductivity using KALCOS-K (Empa, Switzerland) according to ISO 11092
- Vertical fire, according to ISO 15025:2000 (Protection against heat and flame -Method of test for limited flame spread)
- Radiant protective performance, according to ISO 6942:2002 (Protection against heat and fire - Method of test: Evaluation of materials assemblies when exposed to a source of radiant heat)
- Vertical wicking, according to DIN 53 924 (Determination of water absorption velocity of textile fabrics; capillary rise method)
- Liquid moisture management properties using moisture management tester according to AATCC Test Method 195-2009

The sweating guarded hot plate was used to determine thermal resistance and water vapor resistance of fabrics. The quadratic samples (26 cm×26 cm) were placed onto an electrically heated porous plate. The temperature of the measuring plate and the wind velocity was kept constant at 35 °C and 1 m/s, respectively. The ambient conditions were 20 °C and 65% of relative humidity for measuring the thermal resistance, and at 35 °C and 40% of relative humidity for measuring the water vapor resistance of fabrics. Water was supplied to the plate to allow a water vapor flow from the surface though a porous foil. The water vapor resistance was assessed using the heating power supplied to the surface under steady-state conditions. Six tests were conducted for each fabric.

The air permeability was measured using ELPA instrument at a pressure of 100 Pa. By reducing the pressure below atmospheric pressure on one side of the sample using a vacuum pump, air is drawn through the sample and the rate of flow of air is measured. Ten tests were conducted for each fabric.

The Plate Calorimeter KALCOS-K was used to measure thermal conductivity of fabrics. The samples were placed horizontally between a heating and a cooling plate, which were regulated to a constant temperature. The thermal conductivity was assessed using the temperature and heating power of the heating plate, the temperature of the cooling plate, the surface area of the measurement region and the thickness of the sample. This procedure was repeated for three levels of temperature difference between heating and cooling plates over the measured sample. The temperature of the heating plate was set at 36°C and the temperature of the cooling plate was set at 31°C, 28°C and 25°C. A pressure of 2 kN/m^2 was exerted on the samples.The samples were conditioned and tested at 23 ± 2 °C and 50 ± 5 % of relative humidity. Twelve tests were conducted for each fabric. Thermal conductivity (K) was defined as the quantity of heat (Q), transmitted through a thickness (L), in a surface area (A), due to a temperature difference (ΔT), under steady-state conditions using (8):

$$K = \frac{Q \times L}{A \times \Delta T} \quad (8)$$

The IR comfort test (determination of cooling performance and drying time) were conducted using an infrared camera (Thermo Vision A40 M, FLIR Systems, Frankfurt am Main, Germany) [29]. This measurement is based on wetting a fabric on one side with a defined amount of water. Four drops of distilled water with a total weight of approximately 200 ± 2 mg and a temperature of 35 °C were evenly dripped on the surface of the fabric sample. The whole system was placed in a climatic chamber with a controlled temperature of 35 °C, relative humidity of 40% and wind speed of 1 m/s. There are two important distinctive points named as fabric total dry point and fabric total wet point. The $t_{5\%}$value defined as the state that fabric is completely wet and the $t_{95\%}$ value is considered as a state where the fabric is dried fully. Three measurements were taken for each fabric and the average value of drying time was calculated.

The Radiant Protective Performance (RPP) test evaluates the level of protection of a fabric in a situation where the hazard is predominantly radiant, such as an aircraft fuel fire or a wild land fire. In this method, the typical heat flux ranges from 21 kW/m^2 to 84 kW/m^2 [30, 31]. Based on ISO 6942, the conditioned samples were mounted onto a defined curved copper plate calorimeter and exposed to a defined radiant heat source. The time needed for the temperature to rise by 12 °C and 24 °C in the calorimeter was recorded and expressed as radiant heat transfer indexes. Also the difference between two indexes was calculated as the heat transmission factor. The measured time for producing an increase in the temperature of the calorimeter corresponds to the time the person starts to feel pain with second degree burns [31]. The RPP value is the product of the incident heat flux and the recorded tolerance time to a second degree burn ([kW/m^2]). The transmitted heat flux density, Q_c, in kW/m^2, was calculated using (9).

$$Q_c = \frac{\mathrm{M} \times C_p \times 12}{A \times (t_{24} - t_{12})} \tag{9}$$

where M is the mass of the copper plate in kg, C_p is the specific heat of copper [0.385 kJ/kg.ºC], 12/(t_{24}-t_{12}) refers to the mean rate of rise of the calorimeter temperature in ºC/s in the region between a 12 ºC and a 24 ºC rise, and A is the area of the copper plate in m^2.

The heat transmission factor, TF (Q_0), for the incident heat flux density level Q_0 is given by (10):

$$TF\left(Q_0\right) = \frac{Q_c}{Q_0} \tag{10}$$

The standard test method ISO 15025 assesses the properties of fabrics in response to a short contact with a small igniting flame under controlled conditions to determine the flame spread properties of textile fabrics. Six vertically oriented (3 in warp and 3 in weft direction) samples from outside of each fabric were brought into contact with a 40 ± 2 mm long propane flame for a 10 s ignition time. Measurements were made during the length of time that the specimen had been exposed to the flame and the time afterglow; after the flame source had been removed. Char length, or a visible damage to the test specimen after application of a specified tearing force, was determined.

The rate of the water transport was measured according to the vertical strip wicking test [32]. In this test the wicking heights of water at 10, 30, 60 and 300 s on the fabric samples were measured. Ten specimens (5 in warp and 5 in weft direction) were prepared and immersed in distilled water. 15 mm from the lower end of each sample was clamped with a 1.4 g clip, in order to ensure that the fabric sample would contact the water [33].

The Moisture Management Tester (MMT) measures the dynamic liquid transport properties of fabrics. The specimen was horizontally held flat under fixed pressure between the upper and lower concentric surfaces with moisture sensors while standard test solution (0.15 g sodium chloride 0.9%) was introduced onto the center top surface of the fabric (skin side). All of the samples were conditioned and tested at 23 ± 2 °C and 50 ± 5 % RH.

V. Results and Discussion

A. Fabric Porosity

The results of the calculation of fabric porosity are presented in Table II and Fig. 1, which show that the porosity of fabrics increases with increasing the ratio of Kermel fibers in blended fabrics. It seems that the increase in the porosity is related to the increase in the Kermel fibers ratio. This change is due to the difference in linear density which is shown in Table I. The lowered number of fibers in yarn cross-section is a result of difference in linear density of blended fibers, and therefore, it affects the thickness and the porosity of fabrics.

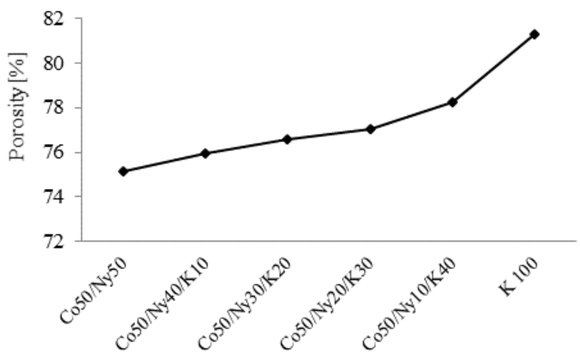

Fig. 1. Porosity of blended fabric samples.

B. Thermal Conductivity

The trapped air in the porous area of fabric structure and the blend ratio of fibers have significant effects on the thermal conductivity of the fabrics (P-value = 0 < 0.05). It is observed in Fig. 2 that by increasing the ratio of Kermel fibers in blends, the thermal conductivity of the fabrics did not show any significant difference. However, at 100% Kermel fiber blend ratio, the lowest thermal conductivity was obtained. This result is attributed to the higher porosity of this fabric sample compared with other fabric samples, and also the inherent Kermel fibers properties.

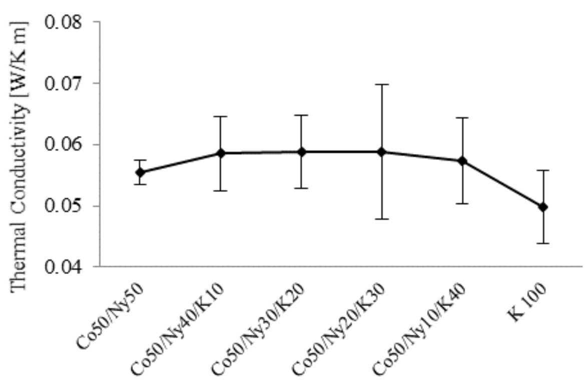

Fig. 2. Thermal conductivity of blended fabric samples.

C. Air Permeability

As shown in Fig. 3 the results indicate that by blending Kermel fibers to cotton/nylon at first the air permeability of sample 2 decreased which was due to an increase in the thickness of the fabric and then air permeability increased with increase in the Kermel fiber content of fabrics, according to the increase in the porosity of the fabrics. The void volume in woven fabrics affects air permeability. In general, at 40% Kermel fiber blend ratio, there is a significant increase in fabric air permeability (P-value = 0 < 0.05).

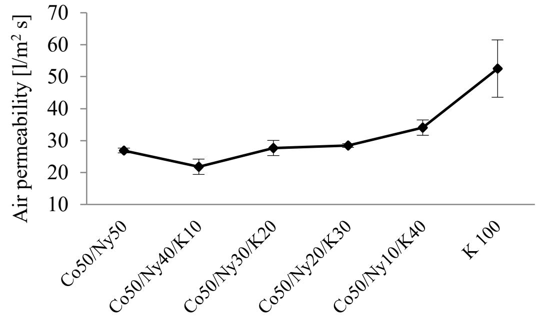

Fig. 3. Air permeability of blended fabric samples.

D. Thermal Resistance

It is clear that thermal resistance of Kermel fibers, and hence, the fabric made from these fibers is considerably higher than that of the cotton and nylon (Table III). As it is shown in Fig. 4, with increasing the ratio of Kermel fibers in blended fabrics, thermal resistance of fabrics increased. However, at 20% and 30% Kermel fiber blend ratio, the thermal resistance values were unchanged. In general, as expected, fabric samples containing a high content of Kermel fiber exhibited the highest thermal resistance. This result is related to the high thermal resistance properties of Kermel fiber.

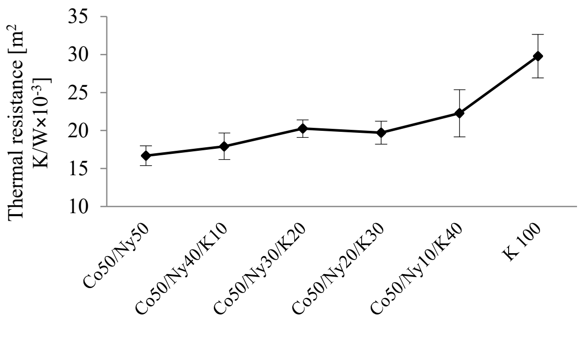

Fig. 4. Thermal resistance of blended fabric samples.

E. Water Vapor Resistance

As shown in Fig. 5, with increase in the Kermel fiber blend ratio up to 40%, the water vapor resistance decreased. This result is apparently attributed to the role of the yarn structure and properties at a mesoscopic level, as well as the fabric porosity as a macroscopic parameter. However, as depicted in Fig. 5, in 100% Kermel fiber sample the water vapor resistance increased. In fact, the inherent Kermel fiber properties as a microscopic parameter play a significant role here which in turn leads to uncomfortable condition for a wearer.

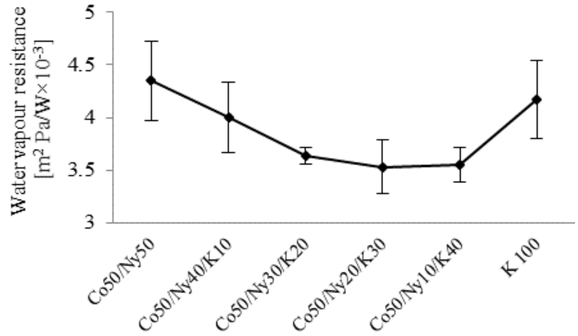

Fig. 5. Water vapor resistance of blended fabric samples.

F. IR Comfort

The IR test is an objective method to evaluate the drying process by measuring the temperature course of a wetted fabric with an infrared camera [29]. The temperature course always shows two important and distinct points: when the fabric is fully wet, and when it is fully dry. The average values of IR test measurements of fabric samples are shown in Fig. 6. According to the table of moisture regain for textile fibers (ASTM D1909-04(2012)) and Kermel fibers specifications [24], nylon 66 and Kermel fibers have the same moisture regain of about 4 to 4.5%. Therefore, samples 1 and 2 showed the same drying time. By increasing the ratio of Kermel in samples 3, 4 and 5 fabric samples, a gradual increase in drying time was observed. It seems that this increase is related to the change of blended yarns and fabrics structures. Nevertheless, all of the fabric samples that contain 50% cotton fibers have similar drying times, which could be explained by natural hygroscopic properties of cotton fibers. Conversely, the 100% Kermel fabric (sample 6) showed the lowest drying time and this sample would be more comfortable when is used as a protective clothing. In general comfort perception, it is more desirable to have a material that dries fast after absorption of liquid moisture. As shown in Fig. 6, the 100% Kermel fabric sample started to dry slightly later than cotton and nylon blended fabric, but it dried much faster. Niedermann *et al.* [29] have studied the correlation between the IR comfort test and the subjective perception of fabric wetness and comfort. They discovered that synthetic-fiber-based fabrics led to a rapid recovery of thermal comfort after preceding wetting, but only when the fabric became fully dry (reached t95%). Yet the cotton fabric allowed a gradual recovery of the comfort already when the $t_{5\%}$ was reached. So, blending cotton with other fibers such as nylon and Kermel in fabric samples used in this study, would lead to a faster comfort recovery for wearers.

G. Thermal Comfort Limit

Based on the comfort limit (4), thermal comfort properties (Table III), assumed ambient temperature of 23 °C, relative humidity of 65% and air velocity of 1m/s [26], the comfort limit for the test fabrics was calculated. The results are shown in Fig. 7. This figure shows the predicted thermal comfort limit of fabric samples plotted against metabolic activity level. It is shown that the predicted thermal comfort limit of cotton/nylon and cotton/nylon - Kermel fabrics show little difference, which can be related to the cotton fiber content of these fabrics. But blending cotton, nylon and Kermel fibers increased the upper comfort limit of produced fabrics. On the other hand, cotton/nylon-Kermel blended fabrics, particularly the sample with 30% Kermel fibers, exhibited the highest upper comfort limit and also the widest range of metabolic activity level. The model predicted that each of the Kermel 100%, cotton/nylon (50/50) and blended fabrics when worn in a hot environment should be perceived thermally comfortable by a wearer who is sweating and is involved in moderate levels of physical activity.

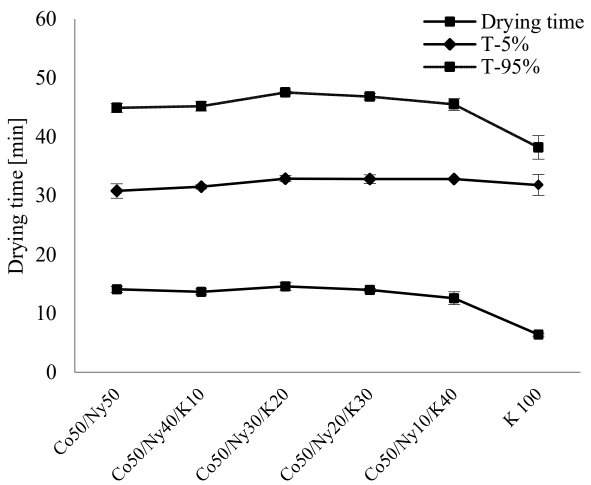

Fig. 6. Values of IR comfort of blended fabric samples.

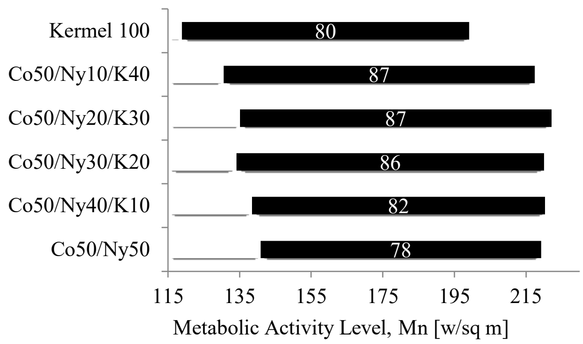

Fig. 7. Thermal comfort limit of cotton/nylon-Kermel blended fabric samples against metabolic activity level.

H. Vertical Fire

Fig. 8 shows the photos of the fabric samples exposed to the test vertical fire. For each fabric sample the test was repeated six times. From these photos it is obvious that an increase in the Kermel fiber ratio in the blended fabrics had a pronounce effect on the prevention of fire diffusion. It is well known that cotton is readily ignited and burns rapidly. Due to extensive shrinking and dripping during combustion, nylon has a self-extinguishing property. Problems arise in blends with natural fibers like cotton which will char and form a supporting structure that will then hold the molten polymer. Kermel fibers are not ignited or burnt, but they provide a coherent char form (without shrinkage) when heated sufficiently to decompose; thus fabrics made from these fibers will continue to be in the charred form as a protective barrier to heat and flame. Because cotton is a highly flammable fiber, the cotton/nylon-Kermel blended fabrics containing 50% cotton are not self-extinguishable. However, if the FR cotton fiber is used and blended with nylon and Kermel fibers, it would be expected that the blended structure be more flame retardant.

The requirements according to the standard test method for clothing to protect against heat and flame are: (1) no sample may continue to burn to the top or the side edges, (2) no sample may have hole formation, (3) no sample may have burning or melting or melting debris, (4) the after flame time shall be ≤ 2 s, (5) the afterglow time must be ≤ 2s; the results show that only sample 6 (Kermel 100%) was completely fulfilling and the other samples that consisted of cotton fibers weren't fulfilling as well.

Fig. 8. Photos of cotton/nylon-Kermel blended fabric samples exposed to vertical fire: a) Sample1 (Co50/Ny50), b) Sample2(Co50/Ny40/K10), c) Sample 3 (Co50/Ny30/K20), d) Sample 4 (Co50/Ny20/K30), e) Sample 5 (Co50/Ny10/K40), f) Sample 6 (K100).

I. Radiant Heat

It can be seen in Fig. 9 that the transmission factor (TF %) of fabric samples against radiant heat flux decreased with increase in the Kermel fibers ratio. This result indicates that Kermel fibers have a significant effect on the radiant protective performance (RPP) value of fabrics (P-value = 0 < 0.05). RPP value, however, is negatively correlated with fabric air permeability. The more porous the fabrics, the easier for radiant heat flow to go through and hence the lower in radiant heat insulation [2]. The results indicate that the cotton/nylon (50/50) fabric showed RPP values close to that of the cotton/nylon-Kermel blended fabrics (even sample 5 with 40% Kermel fiber blend ratio), which is likely attributed to the hollow structure of cotton fiber structure. As obviously shown in Fig. 9, the 100% Kermel fabric sample had the lowest transmission factor, which means this fabric sample had the highest RPP value.

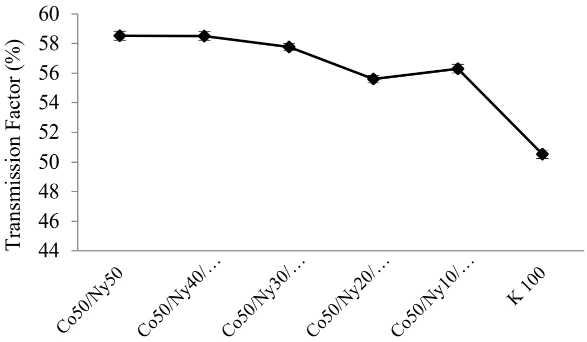

Fig. 9. Radiant Protective Performance (RPP) values (Transmission Factor %) of blended fabric samples.

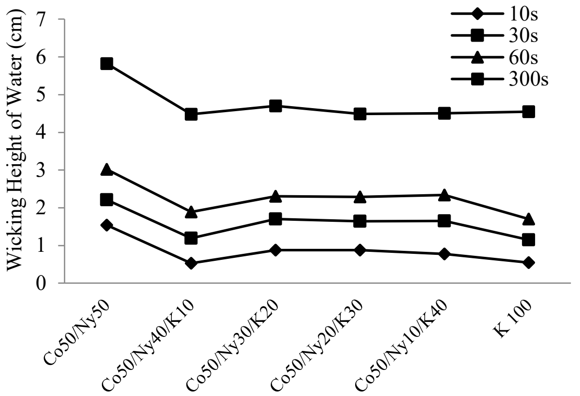

Fig. 10. Wicking height levels of water in blended fabric samples at different rising time of10,30,60 and 300s.

J. Vertical Wicking

As shown in Fig. 10, with increase of the Kermel fiber blend ratio from 10% up to 40%, the wicking height of water compared with cotton/nylon fabric sample decreased. However, increase of Kermel fiber blend ratio from 10 up to 40 percent had no significant effect on the wicking height (P-value = $0 < 0.05$), particularly when the test is conducted for a longer time (after 300 s). Although the Kermel and nylon fibers have the same moisture regain, it seems likely that blending Kermel with cotton and nylon fibers led to changes in structure of the yarn and fabric porosity, as shown in Table I. The increase in the ratio of Kermel fibers in samples increased the fabrics porosity therefore, the changes in the size and number of pores in the structure of blended fabrics prevented water from rising through the fabric. As it is seen in Table I, the 100% Kermel fabric had the highest porosity value among the cotton/nylon-Kermel blended fabrics, and exhibited the lowest wicking height of water, particularly after 60 s.

K. Moisture Management

The one-way-transport capacity (OWTC) of a fabric and its overall moisture management capacity (OMMC) are two important output results of this test. Table III indicates accumulative OWTC index and OMMC of fabric samples, respectively. Sample 3 had the highest one-way-transfer capacity (OWTC = 807.548) and also a high liquid moisture management capacity (OMMC = 0.576). It means that the liquid sweat can be quickly transferred from next-to-the-skin to the opposite side of the fabric to keep the skin dry and provide better thermal comfort. Samples 1, 2, 5 and 6 had low OWTC and OMMC values. On the other hand, these fabric samples showed poor liquid moisture management properties and hence the liquid cannot be absorbed easily from the next-to-the-skin side to the outer surface. Sample 4 had the highest liquid moisture management capacity (OMMC = 0.675) whereas this sample showed the lowest one-way-transfer capacity (OWTC = 456.381).This indicates that the liquid (sweat) can be transferred from the surface next to the skin to the opposite surface but cannot easily evaporate to the environment.

TABLE IV
THE ONE-WAY-TRANSPORT CAPACITY AND OVERALL MOISTURE MANAGEMENT CAPACITY INDEXES OF COTTON/NYLON-KERMEL FABRIC SAMPLES

Sample Number	OWTC [%]	OMMC [-]
1	630.43	0.537
2	545.95	0.398
3	807.54	0.576
4	456.38	0.675
5	636.28	0.448
6	497.80	0.401

VI. CONCLUSION

In this study, the thermal comfort properties of Kermel, cotton/nylon and cotton/nylon blended with Kermel woven fabrics were investigated. The thermal comfort and structural properties of fabrics were characterized in terms of thermal resistance, thermal conductivity, water vapor resistance, air permeability and fabric porosity. Also, the radiant protective performance (RPP) and limited flame protection properties of fabric samples were measured. To confirm the predicted comfort limits by the model, we conducted some additional comfort related experiments such as IR comfort, MMT and wicking tests.

The results have indicated that with increase of Kermel fiber blend ratio, the fabric porosity, the air permeability and the thermal resistance increase. The model have predicted that each of the sample fabrics, when worn in a hot environment, would be perceived thermally comfortable by a wearer involved in moderate levels of physical activity.

The results have also shown that the increase in Kermel fiber ratio in blended fabrics has a pronounced effect on the prevention of fire diffusion. It was observed that Kermel fibers were not ignited or burnt, but they made a coherent char form when heated sufficiently to decompose the material; thus Kermel fabrics continued to be a protective barrier to heat and flame. With increase in the Kermel fibers blend ratio the transmission factor of fabric samples against radiant heat flux decreased, thus the Kermel fibers had a significant effect on RPP.

The result of vertical wicking and MMT tests showed that adding Kermel fibers up to 10% significantly detracted these thermal comfort properties. However, the increase in the Kermel fibers ratio from 10 to 100 percent had no significant effect on wicking as well as moisture management properties.

The results of this work suggest that cotton/nylon (50/10) blended with 40% Kermel fiber leads to thee desirable thermal comfort properties. In addition, blending Kermel fiber at 30% blend ratio with cotton and nylon enhances thermal comfort limit and heat protection of blended fabrics. Also, it would be cost effective if producers use blended fabrics instead of 100% Kermel fabrics in their fire and heat protective clothing productions. In general, only some blends of cotton, nylon and Kermel fibers exhibit proper protection and sufficient thermal comfort properties, related to fiber characteristics, yarn and fabric structure and also complex interaction between physical, mechanical and comfort properties of blend fabrics. Further research work can be done in this area using FR cotton and FR viscose fibers blended with nylon and Kermel fibers.

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