FIBRES & TEXTILES in Eastern Europe
Research Article • DOI: 10.2478/ftee-2023-0039 FTEE • 31(4) • 2023 • 83–89

Comparative Thermal Behaviour Study of Thermal Layers Made Out of Woven and Nonwoven Fabric Using FR Viscose and p-Aramid Fibres

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Abstract
Nine 1/1 plain weave fabric samples were developed using various combinations of low-twist ring spun yarns and rovings of FR viscose, p-aramid, and their blends. The three woven combinations were yarn/yarn, yarn/roving, and roving/roving. These fabric samples were compared for mechanical and thermal properties with needle-punched non-woven fabric samples. The radiant heat transfer index (RHTI24) and convective heat transfer index (HTI24) of the woven and non-woven fabrics were determined. In all samples, the HTI24 - HTI12 and RHTI24 - RHTI12 values were more than 4 seconds, which suggested that there was enough time between experiencing pain and sustaining second-degree burns.

Keywords
Thermal layer, radiative heat resistance, convective heat resistance, fire retardant viscose, p-aramid.

1. Introduction

It is important to note that fire proximity suits are typically designed for short-term exposure to extreme heat and flames, and their performance can vary depending on the specific materials and construction used. These suits provide valuable protection to firefighters and other professionals working in hazardous environments, allowing them to operate with a reduced risk of injury and enabling them to carry out their critical tasks more effectively [1-4].

One of the key components in the construction of fire proximity suits is the outer shell. This outer layer is usually made of a strong and heat-resistant material, such as aramid fibres. Aramid fibers possess exceptional flame resistance and offer excellent protection against thermal hazards [1, 5-7]. They are known for their high strength-to-weight ratio and resistance to tearing, providing firefighters with a robust outer layer of defence. Beneath the outer shell, several additional layers contribute to the suit's overall performance. These layers often include moisture barriers, thermal barriers, and insulating materials [8-10]. The moisture barrier prevents the penetration of liquids, such as water or chemicals, while allowing moisture vapour to escape, thus maintaining comfort and reducing the risk of steam burns. The thermal barrier, usually made of materials like fire-resistant cotton, aramid fibers, or fiberglass, offers insulation against heat transfer. It helps to minimize the transmission of heat to the wearer's body, providing valuable protection [11-13].

The thermal layer in firefighter suits is a crucial component that provides insulation and protection against heat transfer. This layer is designed to minimize the transmission of heat to the wearer's body, reducing the risk of burns and heat-related injuries [14, 15]. The thermal layer is typically made of specialized materials that possess excellent flame resistance and thermal insulation properties. These materials can include fire-resistant cotton, aramid fibres, and fiberglass. Aramid fibers, such as meta- and para-aramids, are also used in the thermal layer of firefighter suits. These synthetic fibers are renowned for their exceptional heat resistance and strength. Aramid fibers do not melt or drip when exposed to high temperatures, making them suitable for firefighting environments. They offer excellent thermal protection, helping to reduce heat transfer to the wearer's body.

Inherently flame-resistant viscose fibre is produced by incorporating fire retardant (FR) additives/fillers in the spinning dope before extrusion. During the burning of this fibre, the flame point produces a lot of nitrous oxides, which effectively isolates the fibre flame point from oxygen, thereby showing a fire-retardant effect. This fibre does not show combustion and will instantly extinct without a fire source with low smoke concentration. Fire retardant viscose is one of the high-performance fibres known for its fire-resistive behaviour [17]. Fiberglass is another material commonly used in the thermal layer of firefighter suits. It is a lightweight and durable material that provides excellent thermal insulation [16-18]. Fiberglass can withstand high temperatures and effectively resist heat transfer, offering an added layer of protection to firefighters. In some firefighter suits, a combination of these materials may be used to optimize the suit's thermal performance, comfort, and durability [16, 19-21].

Thermal layers are mostly manufactured using non-woven-making techniques. The needle-punching technique is one of those widely used [22]. In one study, an aerogel nonwoven thermal liner was developed which showed eight times more thermal resistance than existing commercial reinforcement material and thermal batting material [23].

The non-woven-based thermal barrier layer entrapped air, which acts as a thermal insulator and thus improves thermal resistance properties [24].

In this research, thermal layers using low-twist yarn and roving were developed using para-aramid and FR viscose fibres and compared with non-woven fabrics.

2. Materials and methods

2.1. Fibre

Para-aramid from Dupont and Lenzing's fire-retardant viscose were the fibres used in this study. The physical attributes of each fibre were examined. Tenacity moisture regain, length, elongation, and density are among the qualities that were examined, shown in Table 1.

Fibre properties	FR viscose	p-aramid
Length, mm	51.00	53.00
Tenacity, g/tex	24.21	112.41
Elongation, %	13.78	26.48
Density, g/cc	1.98	1.67
Moisture regain, %	7.11	5.00

Table 1. Physical properties of fibres

S.No	Sample Name	Fibre code	Fabric code
Fabric Structure: Yarn/Yarn			
1	100 % p-aramid	TW 1	TW 1 Y/Y
2	100 % FR viscose	TW 3	TW 3 Y/Y
3	50 % p-aramid + 50 % FR viscose	TW 5	TW 5 Y/Y
Fabric Structure: Yarn/Roving			
1	100 % p-aramid	TW 1	TW 1 Y/R
2	100 % FR viscose	TW 3	TW 3 Y/R
3	50% p-aramid + 50 % FR viscose	TW 5	TW 5 Y/R
Fabric Structure: Roving/Roving			
1	100 % p-aramid	TW 1	TW 1 R/R
2	100 % FR viscose	TW 3	TW 3 R/R
3	50 % p-aramid + 50 % FR viscose	TW 5	TW 5 R/R
Fabric Structure: Non-Woven 330 gsm			
1	100 % p-aramid	TW 1	NW3301
2	100 % FR viscose	TW 3	NW3302
3	50% p-aramid + 50% FR viscose	TW 5	NW3303
Fabric Structure: Non-Woven 665 gsm			
1	100 % p-aramid	TW 1	NW6654
2	100 % FR viscose	TW 3	NW6655
3	50 % p-aramid + 50 % FR viscose	TW 5	NW6656

Table 2. Coding of fibre combinations and various fabric samples

The table shows that the lengths of FR viscose and p-aramid are 51 and 53 mm, respectively. The tenacity for p-aramid was determined to be 112.41 g/tex and 24.21 g/tex for FR viscose. P-aramid and FR viscose showed 26.48% and 13.78% elongation, respectively. Increased elongation is beneficial while spinning yarn. In spinning, lower elongation increased the amount of yarn breakage [25]. Spinning at high speeds is highly challenging with poor elongation. The tenacity of fibres was assessed using an instrument called Vibrodyn, which was used in conjunction with a single fibre fineness tester Vibroscop., The moisture regain was found to be 7.11% for FR viscose and 5%. for p-aramid. Viscose with higher moisture regain will result in more comfortable fabric. The density was found to be 1.98 g/cc for FR viscose and 1.67 g/cc for p-aramid. Because of the use of chemicals to give fire retardancy, FR viscose has a higher density.

2.2. Manufacturing of yarns and roving

Para-aramid and FR viscose were utilized to create 1Ne roving with a 2.5 TPI. This high tpi roving is created for the direct creation of thermal layers using roving rather than turning it into yarn. To complete the investigation, yarn made of 10Ne, FR viscose and p-aramid was also prepared.

2.3. Manufacturing Fabric

15 different fabric combinations were produced, shown in Table 2. Out of these, 9 fabric samples are woven structures and 6 samples are non-woven. The combinations of woven fabrics are: yarn/yarn, yarn/roving, and roving/roving. A CCI sample loom was used to create woven samples. First of all, the warp yarn was sized using a CCI sizing machine. The sizing was done using polyvinyl alcohol (PVA) solution, followed by drying at 100 °C for five minutes. The warping of the sized yarn was done on a CCI warping machine SUU 550. Finally, 1/1 plain weave structure fabric was manufactured on a CCI rapier loom. For weaving purposes the ends/inch and pick/inch were kept at 52/20, 33/13, and 1/16 for fabric samples made out of yarn Combinition-1, Combination-2, and Combination-3, respectively.

Non-woven samples of 330 g/m^2 and 665 g/m^2 were manufactured using a Trytex make needle punching set-up.

2.4. Analysis of fabric

The desized fabric samples developed were examined for areal density, and tensile strength in accordance with ISO 3801 and ISO 5081, respectively. According to ISO 15025, ISO 6942, and ISO 9151 test methodologies, these fabric samples were evaluated for limited flame spread, radiant heat resistance, and convective heat resistance, respectively [17].

The flame spread test was performed using a limited flame spread tester in accordance with ISO 15025 Method A (surface ignition). According to this standard, the surface or bottom edge of the vertically oriented sample is exposed to the appropriate flame for 10 seconds. Data pertaining to the flame spread, hole development, debris formation, after-flame time, and afterglow time is documented.

In order to test the radiant heat transfer index (RHTI24), the ISO 6942 B test technique was used. In accordance with the EN 469 standard for clothing that protects against heat and flame, the textiles were exposed to a radiant heated source that produced heat fluxes of 40 kW/m^2. The amount of time (s) it took for the calorimeter's temperature to increase by (24 ± 0.2) °C was noted. RHTI24 was examined ten times for each sample. Using the following equation, the transmitted heat flux density (Qc), expressed in kW/m^2, was calculated:

$$Q_c = \frac{M.\,C_p.\,12}{A.\,(t_{24} - t_{12})} \quad (1)$$

where M is the copper plate's mass in kilograms; Cp is copper's specific heat of 0.385 kJ/kg at 0 °C; 12/(t24 - t12) is the calorimeter's average rate of temperature rise in decimal degrees per second in the range of 12 to 24 °C rise, and A is the copper plate's area in square meters.

According to the ISO 9151 test technique, the convective heat transmission (HTI24) across a material was calculated. The horizontally oriented test specimen was subjected to an incident heat flux of 80 kW/m^2 from the flame of a gas burner that was positioned beneath it and was partially restricted from moving. A tiny copper calorimeter placed on top of and in contact with the specimen was used to quantify the amount of heat that was going through it. The amount of time (s) it took for the calorimeter's temperature to increase to (24 ± 0.2) °C was noted. For HTI24, each sample was examined ten times.

HTI24 is the time to achieve a temperature rise of 24 °C in the calorimeter at a specified incident heat flux density, which is roughly equivalent to the time it takes to experience a second-degree burn. The HTI12 for radiant and convective heat is the time to achieve a temperature rise of 12 °C in the calorimeter at a specified incident heat flux density. The difference between the two (HTI24-HTI12) is the amount of time it takes for a second-degree burn to develop. A reliable indicator of the skin discomfort warning time was provided by the time disparities between HTI24 and HTI12.

Serial number	Sample Code	Areal Density, g/m^2	Thickness, mm	Tensile Strength, N	
				Warp wise	Weft wise
Combination-1					
1	TW 1 Y/Y	180	1.35	2100	900
2	TW 3 Y/Y	180	1.48	1204	405
3	TW 5 Y/Y	180	1.38	1650	630
Combination-2					
1	TW 1 Y/R	447	1.69	1336	1166
2	TW 3 Y/R	447	1.85	2126	844
3	TW 5 Y/R	447	1.68	2081	1032
Combination-3					
1	TW 1 R/R	721	2.25	1300	2500
2	TW 3 R/R	721	2.34	1713	1931
3	TW 5 R/R	721	2.11	1562	3480

Table 3. Mechanical properties of woven fabrics made out of Combination-1, Combination-2 and Combination-3

Before testing, the specimens were conditioned for at least 24 h at a temperature of (20±2) °C and relative humidity of (65±2) %.

3. Results and discussion

The resultant fabric thickness, tensile strength, and areal density were all examined, and results are shown in Table 3. The table shows that the warp-wise tensile strengths of the sample codes TW 1 Y/Y to TW 5 Y/Y, TW 1 Y/R to TW 5 Y/R, and TW 1 R/R to TW 5 R/R are found to be 1204 N to 2100 N, 1336 N to 2126 N, and 1300 N to 1713 N, respectively. On the other hand, the weft-wise tensile strength of these samples was found to be in the range of 405 N to 900 N, 844 N to1166 N, and 1931 N to 3480 N for samples coded as TW 1 Y/Y to TW 5 Y/Y, TW 1 Y/R to TW 5 Y/R, and TW 1 R/R to TW 5 R/R, respectively. The areal density of the fabric samples made out of all three combinations is also given in Table 3. The fabric made out of yarn Combination-1 had an areal density of 183 g/m^2 to 190 g/m, for Combination-2 447 g/m^2 to 455 g/m^2, and for Combination-3 717 g/m^2 to 725 g/m^2. The thickness of the samples varies from 1.35 to 1.48 mm, 1.68 to 1.85 mm, and 2.11 to 2.34 mm for fabric samples made out of yarn Combination-1, Combination-2, and Combination-3, respectively.

Mechanical properties of the non-woven fabric samples developed are given in Table 4. The properties are divided into two groups – 330 gsm and 665 gsm. From the table, the thickness values of fabric samples of 330 gsm vary from 2.59 to 2.63 mm, while for the 665 gsm group it is from 4.92 to 4.95 mm.

Figure 1 shows the physical appearance of a woven sample made with 100 % kevlar and 100 % FR viscose, respectively. The inherent colour of kevlar fabric is yellow in appearance, while FR viscose, being cellulosic in nature, is completely white.

3.1. Flame spread test

According to EN ISO 15025 (Procedure A), a flame spread test was performed on

S. No.	Sample code	Areal density, g/m^2	Thickness, mm
Non-woven fabric with 330 gsm			
1	NW3301	327	2.36
2	NW3302	334	2.29
3	NW3303	329	2.32
Non-woven fabric with 665 gsm			
1	NW6654	661	4.95
2	NW6655	664	4.94
3	NW6656	662	4.92

Table 4. Mechanical properties of non-woven fabrics

Properties	Requirement as per EN 469	Test results
Flame spread resistance	No specimen shall give flaming to the top or either side edge.	Nil
	No specimen shall give hole formation in any layer	Nil
	No specimen shall give flaming or molten debris	Nil
	The mean value the after flame time shall be ≤ 2 sec.	Nil
	The mean value of the afterglow time shall be ≤ 2 sec.	Nil

Table 5. Flame spread test of all the samples

(a) (b)

Fig. 1. Physical appearance of non-woven samples. a) kevlar, b) FR viscose

all 15 samples. Every sample complies with EN 469 requirements. All samples yielded identical findings, listed in Table 5. The findings of the flame spread tests are in accordance with expectations because all of the fabric samples are made out of inherent flame-retardant material [26].

3.2. Radiant heat and convective heat resistance tests

According to EN 469, the mean radiant heat resistance index ($RHTI_{24}$) for performance level 2 should be ≥18 sec, and $RHTI_{24}$ - $RHTI_{12}$ should be ≥ 4 sec. In contrast, the mean heat transmission index (HTI_{24}) for convective heat should be ≥13 sec, and HTI_{24} - HTI_{12} should be ≥4 sec. Although these values of $RHTI_{24}$ and HTI_{24} as per EN 469 are for a component assembly of all layers of firefighter suits (outer layer, moisture barrier, and thermal liner), only the thermal liner is taken in this study to achieve these values so that a firefighter suit with higher resistance to radiant and convective heat can be developed.

From Table 6, the $RHTI_{24}$ value for yarn/yarn (Combination-1) is found to be 11.4 sec for 100 % p-aramid (TW 1 Y/Y), 9.3 sec for 100 % FR viscose (TW 3 Y/Y), and 10.7 seconds for a blend of 50 % p-aramid and 50 % FR viscose (TW 5 Y/Y The convective heat resistance (HTI_{24}) value of the yarn/yarn combination is found at 9.6 seconds for TW 1 Y/Y, 8.5 seconds for TW 3 Y/Y, and 8.7 seconds for TW 5 Y/Y. In the case of yarn/roving (Combination-2), $RHTI_{24}$ values of the TW 1 Y/R sample are found to be 14.1 seconds and 12.3 seconds for TW 3 Y/R and 12.4 seconds for TW 5 Y/R. The convective heat resistance (HTI_{24}), for the TW 1 Y/R sample is found to be 14.4 seconds, 12.9 seconds for the TW 3 Y/R sample, and 13 seconds for the TW 5 Y/R sample. Table 6 also reveals that in roving/roving (Combination-3), samples TW 1 R/R, TW 3 R/R, and TW 5 R/R showed 19.9 seconds, 18 seconds, and 18.2 seconds of $RHTI_{24}$ values, respectively. The HTI_{24} values of these samples (TW 1 R/R, TW 3 R/R, and TW 5 R/R) were 17.8 seconds, 17.7 seconds, and 15.3 seconds respectively. From this study, it is found that the $RHTI_{24}$ and RHT_{24} values of Combination-3 are higher than for Combination-2 and Combination-1. Higher values were shown because of the increase in thickness due to roving insertion in both directions, increasing heat resistance values. Combination-1 shows the lowest values of $RHTI_{24}$ and RHT_{24} as these samples are made out of yarn only. The $RHTI_{24}$ and RHT_{24} values of Combination-2 are greater than for Combination-1 as this combination has yarn in the warp-wise direction and roving in the weft-wise direction.

Due to the more open structure of roving in nonwoven fabric, as compared to yarn, it entrapped air in the pores and thus provided more thermal resistance [24].

Besides, Combination-3 samples' thickness is higher than for Combination-2 and Combination-3. As per the earlier studies, it was found that the thermal insulation of nonwoven batting materials increases with the batting thickness [27-29].

From Table 6, $RHTI_{24}$ values for the 330 gsm group non-woven composition are found to be 13.7 seconds for NW3301, 15.3 seconds for NW3302,

Sample Code	Mean Heat Resistance Index (Radiative resistance)		Mean Heat Transmission Index (Convective resistance)	
	$RHTI_{24}$	$RHTI_{24}$ - $RHTI_{12}$	HTI_{24}	HTI_{24} - HTI_{12}
Combination-1				
TW 1 Y/Y	11.4	6.5	9.6	6.4
TW 3 Y/Y	9.3	5.2	8.5	6.0
TW 5 Y/Y	10.7	5.1	8.3	5.7
Combination-2				
TW 1 Y/R	14.1	7.8	14.4	8.7
TW 3 Y/R	12.3	6.7	12.9	8.2
TW 5 Y/R	12.4	6.9	13	8.2
Combination-3				
TW 1 R/R	19.9	9.4	17.8	8.4
TW 3 R/R	18.0	8.5	17.7	9.5
TW 5 R/R	18.2	8.0	15.3	8.4
Nonwoven 330 gsm construction				
NW3301	13.7	6.2	14.4	4.6
NW3302	15.3	4.4	11.7	4.3
NW3303	14.6	5.0	12.5	4.5
Nonwoven 665 gsm construction				
NW6654	23.7	10.2	25.9	9.3
NW6655	30.0	9.2	26.3	10
NW6656	27.2	9.5	26.0	9.9

Table 6. Radiative heat resistance and convective heat resistance of yarn by yarn (Y/Y) construction

and 14.6 seconds for NW3303. While convective heat resistance (HTI_{24}) values for the 330 gsm group, are 14.4 seconds for NW3301, 11.7 seconds for NW3302, and 12.5 seconds for NW3303.

In the same Table, $RHTI_{24}$ and HTI_{24} values of the 665 gsm non-woven composition group are also given. The $RHTI_{24}$ values of NW6654, NW6655, and NW6656 are found to be 23.7 seconds, 30.0 seconds, and 27.2 seconds, respectively. While HTI_{24} values of NW6654, NW6655, and NW6656 are found to be 25.9 seconds, 26.3 seconds, and 26.0 seconds.

It is clear from the table that the 665 gsm group has higher thermal resistance values ($RHTI_{24}$ and HTI_{24}) compared to the 330 gsm group. The reason for the higher thermal resistance values is that the thickness and areal density of the 665 gsm group are higher than for the 330 gsm group. Due to this, the thermal resistance values of the 665 gsm group are higher than for the 330 gsm group [27-29].

The study also revealed that the $RHTI_{24}$ and HTI_{24} values of the 665 gsm non-woven composition group are higher than all the woven and 330 gsm groups of nonwoven samples. The reason is clear: due to the higher thickness and areal density, the 665 gsm non-woven composition group showed higher $RHTI_{24}$ and HTI_{24} values.

It is also explicit from Table 6 that the $RHTI_{24}$ and HTI_{24} values of Combination-3 are higher than for the 330 gsm group of samples. The thickness of samples of the Combination-3 and 330 gsm groups, as shown in Table 3 and Table 4, are almost similar. The reason behind these higher values of Combination-3 is that it has a higher areal density compared to the 330 gsm group of samples.

4. Conclusion

The impact of various fiber combinations, yarn types, and fabric constructions on the radiant and convective heat transfer characteristics of the thermal layer were examined in this study. All tests were done according the EN 469 standard. The following conclusions were drawn from the study:

- The instance where both the warp and the weft are comprised of roving was found to have a high level of radiant heat transfer protection in the case of the woven sample, while in the case of the non-woven sample with 665 gsm, it was found to have maximum radiative heat resistance.
- The fabric made entirely of p-aramid offered the highest radiant heat transfer index, or level of radiant heat transfer protection.
- As the thermal liner's thickness increases, the amount of heat radiation and convective heat it can block increases. In the case of the woven fabric, maximum resistance was shown by the roving/roving fabric combination, while in the case of non-woven, maximum resistance was shown by non-woven fabric with 665 gsm.

– The fabric made out of 100 % FR viscose provide protection from radiant and convective heat close to that shown by 100% p-aramid fabric.

All the samples provide more than 4 seconds of escape time from feeling pain to suffering a second-degree burn, as indicated by HTI24 – HTI12 results in both convective and radiant heat. In the case of the R/R construction and non-woven with 665 gsm, the escape time from feeling pain to suffering a second-degree burn is more than 7 seconds.

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