

Development of thermal layer using low twist yarns and roving of aramids and FR viscose blend

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In this study, various fabrics of FR Viscose, m-aramid, and p-aramid have been manufactured using low-twist yarn as well as roving, and then studied for their thermal and mechanical properties. The ring-spinning system is used to manufacture different low-twist yarns and roving. Twenty-one (21) woven fabric samples with 1 up 1 down plain weave using three combinations out of these yarns and roving in warp and weft have been produced. The three combinations are Yarn/Yarn, Yarn/Roving, and Roving/Roving. The radiant heat transfer index (RHTI₂₄) and convective heat transfer index (HTI₂₄) of the fabrics of m-aramid, p-aramid, and FR viscose made out of Yarn/Yarn combination with different blend compositions are found in the range of 7.5–11.4 s and 7.2 – 9.6 s respectively. However, the fabrics made out of Yarn/Roving and Roving/Roving combinations with different blend compositions show radiant heat transfer index and convective heat transfer index in the range of 11.4 – 19.9 s and 10.5–17.7 s respectively. The HTI₂₄ – HTI₁₂ values of all the samples are found to be more than 4 s, which indicates a good escape time from feeling pain to suffering a second-degree burn in both convective and radiant heat. All 21 woven fabrics qualify for the passing criteria of flame spread as per EN 469 standard. Statistical analysis (ANOVA) is carried out using SPSS software in order to establish the correlation between the fabric samples made out of three types of fibres and their blends in the Roving/Roving combination with convective heat and radiant heat properties.

Keywords: Convective heat transfer index, FR viscose, Low-twist yarn, m-aramid, p-aramid, Radiant heat transfer index, Roving

1 Introduction

For the safety of firefighters during rescue operations, protective clothing and other personal protective equipment (PPE) play an important role¹. Firefighters have to undergo various situations², like exposure to a high level of heat & fire hazards, chemical, and biological toxins, etc. Hence, there is a need to balance these complex requirements for the development of firefighter suits that can protect them against possible flame impingement, high air temperatures, hot liquids, steam, radiant heat, and exposure to chemicals³. The outer shell of the firefighter suit should be water, and chemical-resistant with an excellent level of durability. Besides, there is also a need to reduce the heat stress of firefighters during his/her duties caused by clothing and other PPE.

In any fire proximity suit basically, there are four layers, i.e outer layer or shell fabric, mostly this fabric is made up of aramid, polybenzimidazole (PBI), or a compatible blend. Designing is done mainly focusing on

the function, i.e protection from heat and flames, protection from external chemicals and water, and protection against abrasion, cuts, and lacerations. The second layer is the moisture barrier. The function of this layer is to provide protection against the penetration of water, chemicals, and blood-borne pathogens. After the moisture barrier comes to the third layer which is the thermal barrier. This barrier plays a crucial role in the overall performance of the fire suit's assembly¹⁻⁸. Its main properties include providing insulation by creating air cushions and micro-climate chambers within the garment to favour comfort and minimize heat stress, facilitating easy donning/doffing of the garment, and protecting the moisture barrier from any damage coming from the inside part of the garment. After the thermal liner's fourth layer a slick liner will provide a perceived sense of comfort as the wearer won't need to fight with the undergarments in order to put on or move in the suit. This slick liner leads to wicking moisture away from the body to increase the wearer's comfort^{9,10}.

In firefighter suits, mostly inherently flame-resistant materials are used to protect the wearer from high levels of flame and heat exposure during rescue

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operations. The outer shell/layer of the firefighter suit, as well as the thermal layer, is generally constructed using fabric made out of inherently flame-resistant fibres. Sometimes these fibres are blended with other fibres to reduce production costs and improve comfort properties. These high-performance flame-retardant fibres include organic materials but are not limited to aramid including p-aramid, m-aramid, FR viscose, modacrylic, polybenzimidazole (PBI), etc.⁹. Meta-aramid fibre is highly resistant to temperature, chemical degradation, and abrasion. It is manufactured by the wet spinning process¹¹. It is a semi-crystalline fibre with its molecular chain partially oriented along the axis of the fibre. The tenacity of this fibre is about 6.16g /dtex. This can withstand 400°C when exposed to flames and temperatures. On the other hand, para-aramid is manufactured using the dry jet wet spinning method and has high tensile strength and modulus behaviour. It consists of fully extended liquid crystal chains formed along the fiber axis with a high degree of crystallinity which increases the fibre's strength. The tenacity of this fibre is around 25.3 g/dtex and elongation-at-break is about 3.5%. FR viscose is a man-made cellulosic fibre. The flame retardance property of this fibre is achieved by incorporating "phosphorous" in the viscose matrix during fibre spinning stage^{12,13}. The strength of the fibre varies from 18 cN/tex to 25 cN/tex with 13 - 23% elongation. Modacrylic fibres^{11,12} is a chemical fibre that is manufactured using 35 - 85% by weight of acrylonitrile units. Its melting point is about 185°C. It has 3.0–3.5% moisture regain. The specific stress of modacrylic fibre ranges from 15.9 cN/tex to 22.1 cN/tex with 35–40% elongation. The specific gravity of this fibre is 1.37 g/cm³. Polybenzimidazoles (PBI)¹⁴ is a class of extremely heat-resistant heterocyclic thermoplastics. They are prepared from an aromatic tetraamine and an aromatic dicarboxylic acid or a derivative of it. It has a very high glass transition temperature of about 425°C (800°F) and no melting point and its heat deflection temperature at 264 psi (1.8 MPa) is about 815°F (435°C). It also possesses outstanding heat stability and chemical resistance, including alcohols, hydrocarbons, chlorinated solvents, hydrogen sulfide, weak acids and bases, and many other chemicals. Its decomposition temperature is more than 1300°F (> 500°C).

In a firefighter suit, although every layer has its own importance, the outer shell layer and thermal insulation layer play a pivotal role in protecting the wearer's life. Some of the critical parameters of woven shell fabric that affect the thermal protective performance are the

type of fibre, yarn twist, type of composite yarn, fabric thickness, fabric cover, and crimp of the fabric. On the other hand, porosity, fibre denier, areal density, thickness, etc. factors influence the thermal insulation properties of the thermal insulation layer. A number of studies¹⁴⁻¹⁶ have been carried out on the insulation thermal layer. Mostly aramid nonwoven fabric is used for this purpose. It was observed¹⁷ that with the increase of layers of the fabric in the thermal insulation liner, the thermal insulation property was enhanced. The thermal insulation property of any clothing depends on the presence of dead air or still air gap¹⁸⁻²². Increasing layers of clothing increase the still air gap. It is found that if the fire protective clothing system does not have a dead air gap the chances of burn injury increase^{10,15-17}. This type of clothing system also showed lower thermal protective performance (TPP). Studies showed that the TPP values highly depend on air gaps present in the layer or between the layers. These all studies indicated that the importance of dead air gaps play an important role in enhancing the thermal insulation property of the thermal layer. That is the reason, most nonwoven fabric^{18,23} is preferred over woven fabric made out of the loom, as the nonwoven fabric has a high percentage of air gaps. For making nonwoven fabric, there is a need for a set of nonwoven-making machines¹⁹⁻²⁸.

However, very few studies have been carried out on a thermal liner made out of low-twist yarn or roving. The fabric made up of a low twist yarn has more still or dead air gaps. Because of more still air gap in low twist stand, it shows better insulation. This study aims to develop a thermal layer of firefighter suit using low twist yarn and roving of the single and binary composition of m-aramid, p-aramid, and FR viscose fibres to achieve radiant and convective heat resistance properties as per the requirements of firefighter suit specification EN 469²⁴.

2 Materials and Methods

2.1 Fibres

The fibres, selected for the development of the thermal layer, are p-aramid, m-aramid from Dupont, and FR viscose from Lenzing. The results of physical properties, like length, density, tenacity, and moisture regain, of m-aramid, p-aramid, and FR viscose are given in Table 1.

The tenacity of fibres was determined by an instrument called Vibrodyn, which was used in conjunction with single fibre fineness tester Vibroscop.

The higher tenacity of fibres helps during the spinning of yarn, in the weaving process on the loom, and also in higher fabric strength, thus improving the properties in use. The tenacity of para-aramid fibre was found to be very high (112.41 g/tex), while FR viscose fibre's tenacity was found to be the lowest, i.e. 24.21 g/tex amongst all fibres. The tenacity of meta-aramid is 28.26 g/tex. Fibre elongation is also as important as tenacity. This property enables the fibre for further processing of yarns in the spinning process. The elongation % of m-aramid, p-aramid, and FR viscose are found to be 36.2, 26.48, and 13.8 respectively (Table 1).

FR viscose absorbed moisture to a greater extent as compared to other fibres. The moisture regain was measured by taking oven dry weight as per the guideline of BIS 13157. It is clear from Table 1 that FR viscose has the highest moisture regain (7.11%). This property makes this fibre more comfortable to wear. The other fibres, such as m-aramid, and p-aramid, have about 5% moisture regain.

In this study, yarns and rovings were developed from 100% individual fibre as well as their binary and tertiary blends as per Table 2. The coding of these blends is also given in Table 2.

2.2 Manufacturing of Yarns and Roving

Yarn samples (59 tex) were manufactured in a ring-spinning system at the NITRA pilot plant. The spinning condition has been kept the same for all the samples, in order to assure the same yarn structure. The rovings (roving count 590 tex) of all the 7 fibre samples (coded as TW1 - TW7) were also developed with 2.5 TPI. Also, the TPCM of the developed yarn of 59 tex is 5.

2.3 Manufacturing of Fabric

Twenty-one woven samples were developed using three combinations, viz Yarn/Yarn, Roving/Yarn, and Roving/Roving. In all the cases, the warp is sized using a 5 % PVA solution. Sizing paste was prepared by heating and vigorously stirring the solution. Sizing solutions were applied using a CCI sample sizing machine. The sized yarn was dried at 100±5°C and then wound on a cone. The warping of sized yarn is carried out on the CCI sample warping machine (model SUU 550) for making the warping beam. This warping beam was placed on the CCI sample rapier loom (model SL 8900 EG) for making fabric samples of 1 up/1 down plain weave structure. For Yarn/ Yarn construction, the ends/inch (EPI) and pick/inch (PPI) were kept at 52 and 20 respectively. For Yarn/ Roving construction, the EPI was 33, and the PPI was 13. For

Table 1 — Physical properties of fibres

Fibre Properties	m-aramid	p-aramid	FR viscose
Length, mm	51	53	51
Density, dtex	2.63	1.84	2.18
Tenacity, g/tex	28.26	112.41	24.21
Elongation, %	36.25	26.48	13.78
Moisture regain, %	5.5	5.0	7.11

Table 2 — Coding of fibres combinations and developed fabric samples

Sample	Fibre code	Fabric code
Yarn/Yarn		
100 % p-aramid	TW 1	TW 1 Y/Y
100 % m-aramid	TW 2	TW 2 Y/Y
100 % FR viscose	TW 3	TW 3 Y/Y
50% p-aramid + 50% m-aramid	TW 4	TW 4 Y/Y
50% p-aramid + 50% FR viscose	TW 5	TW 5 Y/Y
50% FR Viscose+ 50 % m- aramid	TW 6	TW 6 Y/Y
33.3% p-aramid + 33.3% m-aramid + 33.3% FR viscose	TW 7	TW 7 Y/Y
Yarn/Roving		
100 % p-aramid	TW 1	TW 1 Y/R
100 % m-aramid	TW 2	TW 2 Y/R
100 % FR viscose	TW 3	TW 3 Y/R
50% p-aramid + 50% m-aramid	TW 4	TW 4 Y/R
50% p-aramid + 50% FR viscose	TW 5	TW 5 Y/R
50% FR viscose+ 50 % m- aramid	TW 6	TW 6 Y/R
33.3% p-aramid + 33.3% m-aramid + 33.3% FR viscose	TW 7	TW 7 Y/R
Roving/Roving		
100 % p-aramid	TW 1	TW 1 R/R
100 % m-aramid	TW 2	TW 2 R/R
100 % FR viscose	TW 3	TW 3 R/R
50% p-aramid + 50% m-aramid	TW 4	TW 4 R/R
50% p-aramid + 50% FR viscose	TW 5	TW 5 R/R
50% FR Viscose+ 50 % m- aramid	TW 6	TW 6 R/R
33.3% p-aramid + 33.3% m-aramid + 33.3% FR viscose	TW 7	TW 7 R/R

Roving/Roving construction, EPI and PPI were 13 and 16 respectively. The coding of these samples is given in Table 2.

2.4 Analysis of Fabric

Developed fabric samples were first desized and then analysed for unit area weight as per theoretical calculation method. The tensile strength properties were calculated as per ISO5081^{1,2,4,29}. The sample thickness was analysed as per ASTM D1777. As some fabrics contain p-aramid and m-aramid to avoid cutting error with GSM cutters, areal densities were

calculated with the help of the theoretical method using the following formulas:

$$(i) \text{ GSM} = \text{warp weight/m}^2 + \text{weft weight/ m}^2$$

$$(ii) \text{ Warp weight} = \frac{(\text{EPI} \times 39.37 \times 0.59) \times (100 + \text{Crimp } \%) }{\text{Warp Count (Net)} \times 100}$$

$$(iii) \text{ Weft weight} = \frac{(\text{PPI} \times 39.37 \times 0.59) \times (100 + \text{Crimp } \%) }{\text{Weft Count (Ne)} \times 100}$$

These fabric samples were tested for limited flame spread, radiant heat resistance, and convective heat resistance as per ISO 15025, ISO 6942, and ISO 9151 test methods respectively¹². The ends and picks per unit length were counted after preparing the sample from the loom in a relaxed state.

A limited flame spread test was carried out using a limited flame spread tester of Wazau, Germany as per ISO 15025 Method A (surface ignition) for vertically oriented samples. In this standard, the specified flame is applied for 10 s to the surface or the bottom edge of the vertically oriented sample. The information related to the spread of flame, hole formation, formation of debris, after-flame time, and afterglow time is recorded.

ISO 6942 B test method was followed to test the radiant heat transfer index (RHTI₂₄). The fabrics were exposed to a radiant heated source emitting 40 kW/m² heat fluxes as per the EN 469 standard for clothing to protect against heat and flame. In the test, Wazau, Germany radiant heat tester was used. The time (s), for the temperature in the calorimeter to rise (24 ± 0.2) °C is recorded. Each sample was tested 10 times for RHTI₂₄. The transmitted heat flux density (Q_c) in kW/m², was determined using the following equation:

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

where M is the mass of the copper plate in kg; C_p , the specific heat of copper 0.385 kJ/kg °C; 12/ ($t_{24} - t_{12}$), the mean rate of rising of the calorimeter temperature in °C/s, in the region between 12°C and 24°C rise; and A , the area of copper plate in m².

The convective heat transmission (HTI₂₄) through material is determined as per the ISO 9151 test method using a convective heat tester supplied by Wazau, Germany. The horizontally oriented test specimen is partially restrained from moving and subjected to an incident heat flux of 80 kW/m² from the flame of a gas burner placed beneath it. The heat passing through the specimen is measured using a small copper calorimeter on top of and in contact with the specimen. The time

(s), for the temperature in the calorimeter to rise up to (24 ± 0.2) °C is recorded. Each sample was tested 10 times for HTI₂₄.

The HTI₁₂ for radiant and convective heat is a time to achieve a temperature rise of 12°C in the calorimeter at a specified incident heat flux density—this time is a rough measure of the time before pain is experienced and HTI₂₄ is a time to achieve a temperature rise of 24°C in the calorimeter at a specified incident heat flux density—this is roughly equal to the time it takes to suffer a second-degree burn. The difference between the two (HTI₂₄ and HTI₁₂) is an escape time from feeling pain to suffering a second-degree burn²⁹. The time differences between HTI₂₄ and HTI₁₂ gave a good indicator of the skin pain alarm time.

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

2.5 Statistical Analysis

Experimental data were analyzed using SPSS (version 25) to establish a relationship between various results. Multivariate ANOVA was used to compare means. The null hypothesis (Ho) is that there is no relationship between the fabric samples made out of three types of fibres and their blends (Coded as TW1, TW2, TW3, TW4, TW5, TW6, and TW7) in Roving/Roving combination with convective heat and radiant heat properties. In the alternative hypothesis, there is a relationship between the three types of fibres and their blends with convective heat and radiant heat properties. Ho will be rejected when the p-value turns out to be less than a pre-determined significance level, i.e. 0.05.

3 Results and Discussion

3.1 Mechanical Properties

The produced fabrics were analyzed for their areal density, tensile strength, and tear strength. Results are given in Table 3. From the table, it is clear that the tensile strength of the sample codes TW 1 Y/Y to TW 7 Y/Y, TW 1 Y/R to TW 7 Y/R, and TW 1 R/R to TW 7 R/R are found to be 1204 to 2100, 1550 to 2126 and 1300 to 1862 respectively

3.2 Flame Spread Test

All 21 samples were tested for flame spread test as per EN ISO 15025 (Procedure A). All the samples meet the requirement of EN 469. The results of all the samples were the same and reported in Table 4. As all the fabric samples are made out of inherent FR fibres,

the results of flame spread tests are on the expected line.³⁰

3.3 Radiant Heat and Convective Heat Resistance Tests

As mentioned earlier, three sets of experiments have been designed using Yarn/Yarn, Yarn/Roving, and Roving/Roving constructions. In all the experiments, woven fabric samples are tested for radiant and convective heat resistance as per ISO 6942 and ISO 9151 respectively. As per EN 469, for performance level 2, the mean radiant heat resistance index (RHTI₂₄) should be ≥ 18 s, and for RHTI₂₄ - RHTI₁₂ it should be ≥ 4 s. On the other hand, in the case of convective heat, the mean heat

transmission index (HTI₂₄) should be ≥ 13 s, and for HTI₂₄ - HTI₁₂ it should be ≥ 4 s. Although these values of RHTI₂₄ and HTI₂₄ as per EN 469 are for a component assembly of all the layers (outer layer, moisture barrier, and thermal liner) of firefighter suits, in this study, only thermal liner is taken to achieve these values so a firefighter suit with higher resistance to radiant and convective heat can be developed.

3.3.1 Yarn by Yarn (Y/Y) Construction

Table 5 shows that the value of RHTI₂₄ of the sample TW 1 Y/Y is 11.4 s and found to be higher than other samples. The higher RHTI₂₄ of TW 1 Y/Y may be due to the fact that it is made from 100% p-aramid. It is a well-known fact that p-aramid has high heat resistance properties compared to m-aramid and FR viscose fibres. The results of m-aramid and p-aramid are also supported by the reading of specific heat given in the literature of the Dupont data sheet. As per the Dupont data sheet, Kevlar (p-aramid), shows a specific heat of 0.34 cal/g °C, which is higher than the specific heat of Nomex (m-aramid), which is

Table 3 — Mechanical properties of fabrics

Sample code	Areal density g/m ²	Thickness mm	Tensile strength, N	
			Warp-wise	Weft-wise
Yarn/Yarn				
TW 1	180	1.35	2100	900
TW 2	180	1.30	1834	600
TW 3	180	1.48	1204	405
TW 4	180	1.35	2093	850
TW 5	180	1.38	1650	630
TW 6	180	1.42	1508	534
TW 7	180	1.39	1906	545
Yarn/ Roving				
TW 1	447	1.69	1336	1166
TW 2	447	1.75	1600	1100
TW 3	447	1.85	2126	844
TW 4	447	1.70	1550	1058
TW 5	447	1.68	2081	1032
TW 6	447	1.92	1945	967
TW 7	447	1.88	1963	1155
Roving/ Roving				
TW 1	721	2.25	1300	2500
TW 2	721	2.19	1343	2188
TW 3	721	2.34	1713	1931
TW 4	721	2.22	1862	2591
TW 5	721	2.11	1562	3480
TW 6	721	2.26	1450	2100
TW 7	721	2.27	1352	3398

Table 4 — Flame spread test of all the samples

Properties	Requirement as per EN 469	Test results
Flame spread resistance	No specimen shall give flaming to 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 after flame time shall be ≤ 2 s.	Nil
	The mean value of afterglow time shall be ≤ 2 s.	Nil

Table 5 — Radiative heat-resistant and convective heat-resistant Yarn by yarn (Y/Y) construction

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
Yarn/Yarn				
TW 1	11.4	6.5	9.6	6.4
TW 2	8.3	4.7	9.3	6.3
TW 3	9.3	5.2	8.5	6.0
TW 4	8.7	4.2	8.8	4.7
TW 5	10.7	5.1	8.3	5.7
TW 6	10.6	4.1	8.4	6.9
TW 7	8.9	4.3	7.4	4.9
Yarn/Roving				
TW 1	14.1	7.8	14.4	8.7
TW 2	11.4	6.3	10.2	6.9
TW 3	12.3	6.7	12.9	8.2
TW 4	12.2	6.9	11.9	7.0
TW 5	12.4	6.9	12.9	8.2
TW 6	11.8	7.0	12.0	7.7
TW 7	11.7	6.1	10.5	6.6
Roving/Roving				
TW 1	19.9	9.4	17.8	8.4
TW 2	14.4	7.4	11.8	7.2
TW 3	18.0	8.5	17.7	9.5
TW 4	16.2	8.7	14.1	8.0
TW 5	18.2	8.0	15.3	8.4
TW 6	16.3	8.1	13.6	8.5
TW 7	17.8	7.6	13.7	8.3

0.26-0.29 cal/g °C at 25 °C. The $RHTI_{24}$ of TW 2 Y/Y (100% m-aramid) is found to be lower than the TW 3 Y/Y (100% FR viscose), the lower radiant heat value of TW 2 Y/Y may be due to its lower thickness (1.30 mm) as compared to TW 3 Y/Y (1.48 mm). It is clear that if m-aramid is blended with p-aramid and FR Viscose, the overall $RHTI_{24}$ value decreases from that of the 100% p-aramid. The $RHTI_{24}$ value of secondary blends of p-aramid is lower than the $RHTI_{24}$ value of 100% p-aramid (TW 1 Y/Y), despite the secondary blends of p-aramid TW 4 Y/Y and TW 5 Y/Y having a higher thickness of 1.35 mm and 1.38 respectively. This is due to the fact that the $RHTI_{24}$ values of TW 2 Y/Y (100% m- aramid) and TW 3 Y/Y (100% FR Viscose) are 8.3 and 9.3 s respectively, which are lower than the $RHTI_{24}$ value of TW 2 Y/Y (100% p-aramid). Similarly, the tertiary blend of p-aramid TW 7 Y/Y is also having a lower $RHTI_{24}$ value than 100% p-aramid (TW 1 Y/Y). The blend of 50% m-aramid and 50% FR viscose (TW 4Y/Y) shows 8.7 s of $RHTI_{24}$ value, which lies between $RHTI_{24}$ values of 100% m-aramid (TW 1 Y/Y) and 100% FR Viscose (TW 3 Y/Y). The table also provides the results of the difference between $RHTI_{24}$ and $RHTI_{12}$. The difference among all the samples is found between 4.1 s and 6.5 s.

The convective heat resistance results in heat transmission index (HTI_{24}) values of all the samples are given in Table 5. The HTI_{24} values of TW 1 Y/Y (p-aramid), TW 2 Y/Y (m- aramid), and TW 3 Y/Y (FR Viscose) are 9.6 s, 9.3 s, and 8.5 s respectively. It is found that with the addition of FR viscose in the blend, HTI_{24} values are decreasing. It is also clear that no sample meets the requirement of radiant heat transfer index ($RHTI_{24}$) and convective heat transfer index (HTI_{24}) as per EN469. In all the cases, samples meet the requirements of HTI_{24} - HTI_{12} for both radiant and convective heat. Previous studies have also supported these results.^{12, 31}

3.3.2 Yarn by Roving (Y/R) Construction

In the second set of experiments yarn by low-twist strand (Roving) woven fabric compositions are taken into consideration. In this composition, yarn is taken in the warp direction and a low twist stand (Roving) is taken in the weft direction.

The $RHTI_{24}$ values of all the fabrics are given in Table 5. The results vary from 11.4 s to 14.1 s. From the table, the value of $RHTI_{24}$ of the sample TW 1 Y/R (p-aramid) is 14.1 s and found to be higher than other samples. The $RHTI_{24}$ of TW 2 Y/R (100% m-aramid) is lower than the $RHTI_{24}$ of TW 3 Y/R (100%

FR viscose), which may be due to its lower thickness (1.69 mm) as compared to TW 3 Y/R (1.85 mm).

From the table, it is clear that the $RHTI_{24}$ value of secondary blends of m-aramid with p-aramid and FR viscose is lower than the $RHTI_{24}$ value of 100% p-aramid (TW 1 Y/R), despite the secondary blends of m-aramid TW 4 Y/R and TW 6 Y/R are having higher thickness of 1.77mm and 1.92 respectively. This is due to the fact that the $RHTI_{24}$ values of 100% m-aramid (TW 1 Y/R) and TW 3 Y/R (100% FR Viscose) are 11.4 s and 12.3 s respectively, which are lower than the $RHTI_{24}$ values of TW 1 Y/R (100% p-aramid). Similarly, the tertiary blend of m-aramid, p-aramid, and FR viscose (TW 7 Y/R) is also having a lower $RHTI_{24}$ value than 100% m-aramid (TW 2 Y/R). The blend of 50% m-aramid and 50% FR viscose (TW 6 Y/R) showed 11.8 seconds of $RHTI_{24}$ value, which lies between $RHTI_{24}$ values of 100% m-aramid (TW 1 Y/R) and 100% FR viscose (TW 3 Y/R).

The $RHTI_{24}$ - $RHTI_{12}$ values of all the samples are found between 6.1 s and 7.8 s. The heat transfer index due to convective heat (HTI_{24}) values of all the samples are also given in Table 5, which varies between 10.2 s and 14.4 s. The higher HTI_{24} value is obtained in TW 1 Y/R, as it is made out of 100% p-aramid fibre. It is also clear that no sample meets the requirement of the radiant heat transfer index ($RHTI_{24}$) as per EN469. Only one sample TW 1 Y/R meets the requirement of the convective heat transfer index as per EN 469. In all the cases, samples meet the requirements of HTI_{24} - HTI_{12} for both radiant and convective heat.

3.3.3 Roving by Roving (R/R) Construction

In the third set of experiments, roving is taken during weaving in both warp and weft directions. The $RHTI_{24}$ values of all the fabrics made out of rovings are given in Table 5. The results of $RHTI_{24}$ values vary from 16.2 s to 19.9 s. The table shows that the value of $RHTI_{24}$ of the sample TW 1 R/R (p-aramid) is 19.9 s and it is found to be higher than those of other samples. The $RHTI_{24}$ of TW 2 R/R (100% m-aramid) is lower than the $RHTI_{24}$ of TW 3 R/R (100% FR viscose), which may be due to its lower thickness (2.25 mm) as compared to TW 3 R/R (2.34 mm).

It is observed that the $RHTI_{24}$ value of secondary blends of p-aramid with m-aramid and FR viscose is lower than the $RHTI_{24}$ value of 100% p-aramid (TW 1 R/R), despite the secondary blends of p-aramid TW 4 R/R and TW 5 R/R are having a higher thickness of

Table 6 — Multivariate ANOVA among three types of fibres and their blends with convective and radiant heat properties

Source	Dependent variable	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	Convective	204.186 ^a	5	40.837	33.070	0.000
	Radiant	125.508 ^b	5	25.102	17.319	0.000
Intercept	Convective	13431.875	1	13431.875	10877.080	0.000
	Radiant	17734.046	1	17734.046	12235.859	0.000
type	Convective	204.186	5	40.837	33.070	0.000
	Radiant	125.508	5	25.102	17.319	0.000
Error	Convective	66.683	54	1.235		
	Radiant	78.265	54	1.449		
Total	Convective	13624.270	60			
	Radiant	17885.440	60			
Corrected Total	Convective	270.870	59			
	Radiant	203.773	59			

^a R Squared = 0.754 (Adjusted R Squared = 0.731).

^b R Squared = 0.616 (Adjusted R Squared = 0.580).

2.22 mm and 2.16 mm respectively. This may be due to lower RHTI₂₄ values of TW 2 R/R (100% m-aramid) and TW 3 R/R (100% FR viscose) than the RHTI₂₄ value of TW 1 R/R (100% p-aramid). Similarly, the tertiary blend of p-aramid TW 7 R/R is also having a lower RHTI₂₄ value than 100% p-aramid (TW 2 R/R). The blend of 50% m-aramid and 50% FR viscose (TW 6 R/R) shows 16.3 s of RHTI₂₄ value, which lies between RHTI₂₄ values of 100% m-aramid (TW 1 R/R) and 100% FR viscose (TW 3 R/R). The RHTI₂₄ - RHTI₁₂ values of all the samples are found between 6.4 and 9.4 s.

The heat transfer index due to convective heat (HTI₂₄) values of all the samples are also given in Table 5, which varies between 7.4 s and 17.8 s. The higher HTI₂₄ value is obtained in TW 1 R/R, as it is made out of 100% p-aramid fibre.

From the table, it is also clear that TW 1 R/R, TW 3 R/R, TW 5 R/R, and TW 7 R/R samples meet the requirement of the radiant heat transfer index (RHTI₂₄) as per EN469. All the samples meet the requirements of the convective heat transfer index as per EN 469. In all the cases, samples meet the requirements of HTI₂₄ - HTI₁₂ for both radiant and convective heat, and values are found more than 7 s.

As per the results shown in Table 6 for multivariate ANOVA among three types of fibres and their blends with convective heat and radiant heat properties, the null hypothesis (Ho) is rejected, as the pre-determined significance level (p-value) is less than 0.05. It indicates that there is a relationship (ANOVA) among the three types of fibres and their blends with convective heat and radiant heat properties. The regression coefficient (R²) values are 0.75 and 0.61 respectively for convective and radiant heat properties.

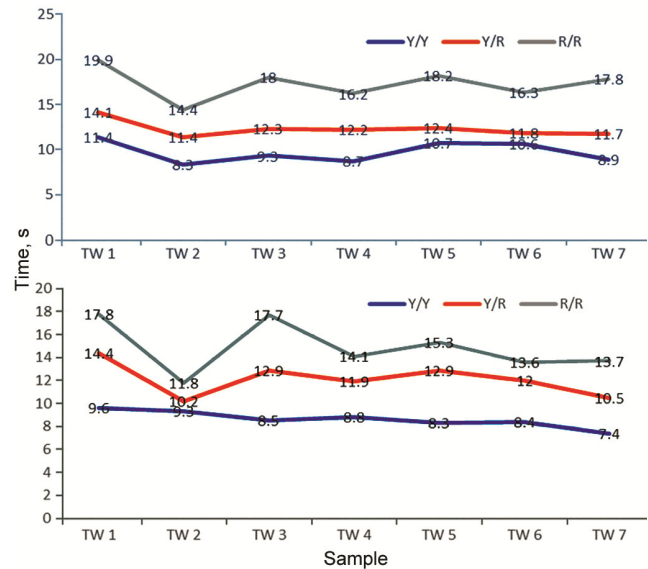


Fig. 1 — Comparison of (a) radiative and (b) convective heat transfer index (RHTI₂₄) among three sets of experiments

3.3.4 Comparison among Three Sets of Experiments

The comparison of radiant heat transfer index values among the three types of constructions of all the twenty-one samples is shown in Fig. 1(a). From the figure, it is clear that the fabric construction having both sides rovings (Roving/Roving), gives higher RHTI₂₄ values as compared to Yarn/Yarn and Yarn/Roving. In all three types, higher values of RHTI₂₄ are found in the 100% p-aramid-based constructions of TW 1 Y/Y, TW 1 Y/R, and TW 1 R/R as compared to other fabric samples of particular types of construction. The values of RHTI₂₄ of TW 1Y/Y, TW 1 Y/R, and TW 1 R/R are 11.4 s, 14.1 s, and 19.9 s respectively.

Figure 1 (b) shows the results of the convective heat transfer index (HTI₂₄) of all twenty-one samples of

three types of constructions. From the figure, it is clear that the fabric construction having both sides rovings (Roving/Roving), gives higher HTI_{24} values as compared to Yarn/Yarn and Yarn/Roving. In all three types, higher values of HTI_{24} are found in the 100% p-aramid-based constructions of TW 1 Y/Y, TW 1 Y/R, and TW 1 R/R as compared to other fabric samples of particular types of construction. The values of HTI_{24} of TW 1Y/Y, TW 1 Y/R, and TW 1 R/R are 9.6 s, 14.4 s, and 17.8 s respectively.

4 Conclusion

In this study, the effects of different material combinations, yarn, and fabric constructions on radiant and convective heat transfer properties of the thermal layer of firefighter clothing have been investigated. The following inferences are drawn:

4.1 A high level of radiant heat transfer protection is found in the case when both warp and weft are made out of roving.

4.2 The 100% p-aramid-based fabric provides the highest value of radiant heat transfer index, i.e. highest protection from radiant heat transfer.

4.3 On increasing the thickness of the thermal liner, the protection from radiant and convective heat increases.

4.4 The fabric made out of 100% FR viscose protects from radiant and convective heat near the 100% m-aramid fabric.

4.5 In the Y/Y fabric construction, no sample meets the requirement of radiant heat transfer index ($RHTI_{24}$) and convective heat transfer index (HTI_{24}).

4.6 In the case of Y/R fabric construction, no sample meets the requirement of the radiant heat transfer index ($RHTI_{24}$). Only one sample (TW 1 Y/R) meets the requirement of the convective heat transfer index.

4.7 In R/R fabric construction, TW 1 R/R, TW 3 R/R, TW 5 R/R, and TW 7 R/R samples meet the requirement of the radiant heat transfer index ($RHTI_{24}$). All the samples meet the requirements of the convective heat transfer index.

4.8 The results of all the samples for $HTI_{24} - HTI_{12}$ (both convective and radiant heat) are more than 4 s. This indicates that the wearer will have more than 4 s of escape time from feeling pain or suffering a second-degree burn during the fire accident. In the case of R/R construction, the escape time from feeling pain or suffering a second-degree burn is more than 7 s.

4.9 As per the statistical analysis (multivariate ANOVA) there is a correlation among the fabrics (Roving/Roving combination) made out of three types of fibres p aramid, m aramid, and FR viscose and their blends with convective heat and radiant heat properties.

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