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Thermal, mechanical and comfort performance of various modacrylic fibre blended fabric

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In this study, various blended fabrics of modacrylic fibre with flame retardant (FR) viscose, and Nylon 66 have been manufactured and studied for their thermal, mechanical and comfort properties for workers of oil & gas industry. The ring spinning system is used to manufacture three sets of yarns. In the first set, three yarns are produced using only modacrylic, only FR viscose, and only Nylon 66 fibres. The second set of yarns is made using blends of FR viscose and modacrylic. These fibres are blended in three different ratios of 30:70, 50:50 and 70:30 for making yarns. The third set is made out of tertiary blends of FR viscose, nylon 66 and modacrylic. These are blended in two different ratios of 30:20:50 and 50:20:30 respectively. Fabric samples have been produced out of these yarns and evaluated for their flame, thermal and mechanical properties after 5 and 50 washes. The radiant heat transfer index and convective heat transfer index of blends of modacrylic fibre are found in the range 12 - 13.5 s and 5.0 - 5.7 s respectively. Multivariate test analysis has been applied to find out the effect of different fibre blends on various flame and thermal properties. The study shows that flame and thermal resistant properties are influenced by fibre blending ratio.

Keywords: Comfort properties, Convective heat transfer index, Flame retardant viscose, Limiting oxygen index, Mechanical properties, Modacrylic, Nylon 66, Radiant heat transfer index, Thermal properties, Viscose

1 Introduction

The application of protective clothing helps to reduce hazardous factors at work. This clothing sometimes becomes an essential and only solution to protect the individual from hazards. The protective clothing are hazards specific. These hazards can vary from one workplace to another. Hazards may be due to heat, flame, electric shocks, electromagnetic radiation, etc. Each type of these hazards needs a specific type of protective clothing. So there is a need for appropriate materials that can work as a barrier for specific hazards.

Mostly 30% of the body is covered by protective clothing used in the military, sports and industry[1]. In some of the cases, this percentage increases up to 100%, for example in fire fighter suits, NBC (nuclear, biological, and chemical) suits, etc. Although protective clothing is vital to protect from hazards, it also adds to physiological loads that could contribute to a progressive decline in the physical and mental capacity of the wearer[2-4]. This adversely affects the productivity and performance of individuals[2, 3]. Therefore, the comfort factor in clothing is also required to maintain individual performance during work.

Fire hazards are one of the most life-threatening hazards. The textile material acts as fuel during a fire accident. It is well-known fact that the majority of fire accidents occur due to these textiles. To protect from this hazard, clothing made out of inherent flame retardant (FR) fibres or FR chemical treated[5-7] fabric is used. FR chemical-treated fabrics are mostly not durable and their flame retardant property decreases with repeated washing. On the other hand, inherent FR fibres, like aramids, FR-viscose, modacrylic, etc[8], are durable in FR property. Modacrylic fibres is a chemical fibre which is manufactured using less than 85% (minimum 35%) by weight of acrylonitrile units and has excellent chemical, sunlight and flame resistance. The modacrylic fibre melts at around 180–185 °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 elastic recovery of modacrylic fibre is around 88% at 4% deformation[9,10]. The specific gravity of this fibre is 1.37 g/cm^3. Being a self-extinguishing fibre, it has wide application in flame retardant workwear.

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FR viscose is a man-made cellulosic fibre that is flame retardant by incorporating “phosphorous” in the viscose matrix. The phosphorous flame retardant is incorporated at the fibre spinning stage. The strength of the fibre varies from 18 cN/tex to 25 cN/tex with 13 - 23% elongation[11].

Nylon 66 is made out of two monomers, each consisting of six carbon atoms, hexamethylenediamine and adipic acid, due to which it is called nylon 66. It has excellent tensile strength and abrasion resistance. Its melting point is 258°C and moisture regain is around 3.8%[12].

During the production of oil and gas, the risk of ignition of combustion gases or oil is very high due to electrical spark, the hot surface of machine parts, etc. The ignition of these gases and oils sometimes causes fire accidents, which are very common in the oil & gas industry[13]. These accidents result in severe burns injuries to the workers and sometimes cause the death of workers. As functional clothing, the thermal protection performance of clothing of workers working in the oil & gas industrys’ is the most important, followed by comfort performance. Various types of workwear made out of aramid, modacrylic, FR finished material, etc are being used to protect workers from fire hazards. Mostly ISO 11612 standard[14] is used to adjudge the quality of these types of workwear. Although safety is the prime requirement for such type of workwear, comfort and durability also play an important role in the selection of such workwear.

To make a balance between these properties, in this study, modacrylic fibre is blended with FR viscose and nylon 66. Nylon 66 is found to be having excellent abrasion resistance and durability properties[15, 16], so it gives excellent wear life to the fabric. The comfort properties of any synthetic fibre made clothing can be improved upon by adding cellulose-based fibres or some engineered synthetic fibre in the blend. Blending modacrylic fibres with FR-viscose fibres may be one of the options for improving the comfort property of the resultant fabric. The study aims to develop blended fabrics of various blends of modacrylic fibre with FR viscose and nylon 66 fibres to achieve thermal, wear and comfort properties as per the requirements of workers working in the oil and gas industry. These blended fabrics are evaluated for safety (heat & flame), comfort and durability properties.

2 Materials and Methods

Modacrylic, FR viscose and Nylon 66 were sourced from M/s JCT Ltd, Lenzing Fibres, Invista respectively and their properties were evaluated as shown in Table 1. These properties, such as length, denier, tenacity, elongation and moisture regain were tested using ISO 6989, ASTM D 1577, ISO 5079 and IS 199 standard test methods respectively.

2.1 Yarn Spinning

These fibres were spun individually and blended in different proportions to improve upon flame-retardant properties, comfort and durability. The blend percentages along with codes are given in Table 2. A ring frame machine of M/s Laxmi Rieter was used

Table 1 — Fibre properties

Parameters	Modacrylic	FR Viscose	Nylon 66
Length, mm	40	51	38
Density, denier	2.06	1.98	1.60
Tenacity, g/tex	25.83	23.28	48.51
Elongation, %	25.29	12.67	27.46
Moisture regain, %	2.01	9.11	3.69

Table 2 — Blend percentages and yarn properties

Fibre	Blend ratio	Code	Tenacity, g/tex	Elongation, %	Actual twists multiplyer TM	Yarn unevenness U%
Modacrylic	100	Ma	13.4	18.0	4.02	8.6
FR Viscose	100	V	12.2	7.8	3.58	8.4
Nylon 66	100	Ny	26.1	21.0	3.80	8.2
FR Viscose: modacrylic	30/70	VMa-37	14.2	12.0	4.02	9.0
FR Viscose: modacrylic	50/50	VMa55	15.1	13.1	3.58	8.8
FR Viscose: modacrylic	70/30	VMa73	14.5	11.9	4.02	8.6
FR Viscose: nylon 66: modacrylic	50/20/30	VNyMa523	13.5	9.1	3.80	9.1
FR Viscose: nylon 66: modacrylic	30/20/50	VNyMa325	12.3	15.5	3.58	9.2

to develop ring spun yarns with a 20s count with 16 Twist Per Inch (TPI). These yarns were tested for their physical properties, such as tenacity and elongation following the ISO 2062 test method using USTER Tansorapid instrument. The yarn twist multiplier (TM) is determined using ISO 2061 and yarn evenness was tested by ISO 16549. The actual TM of yarn determined after manufacturing each type of yarn is given in Table 2 along with yarn unevenness.

2.2 Fabrics Preparation and their Evaluation

Yarns (20s) count so developed were used to manufacture fabric samples (Fig. 1) using the same yarn in warp and weft. For study purposes, only plain weave was selected. Plain ripstop weave with ends/inch 80 and picks/inch 60 were weaved on CCI's automated sample rapier loom. These fabric samples were then washed with hot water for 30 min to remove sizing chemicals followed by heat setting (depending upon the fibre type except FR viscose) in the laboratory curing chamber. Finally, the fabrics were evaluated using standard test methods for various mechanical, heat & flame retardant and comfort properties after giving 5 and 50 washes followed by a tumble drying measured according to ISO 6330-2A. All the heat & flame retardant and mechanical related properties were evaluated by considering ISO 11612 standard used for workwear clothing. The tests were not performed on unwashed fabric samples as per the instruction of ISO 11612. The selection of 50 washes is based on the Indian oil & gas industry specification, in which the fabric should pass the requirements mentioned in the ISO 11612 after 50 washes.

Fabric mass in g/m^2, tensile strength, tear strength, thickness and Taber abrasion were evaluated using ISO 3801, ISO 13934-1, ISO: 13937-2, ISO 5084 and ASTM D 3884 test methods respectively. In the Taber

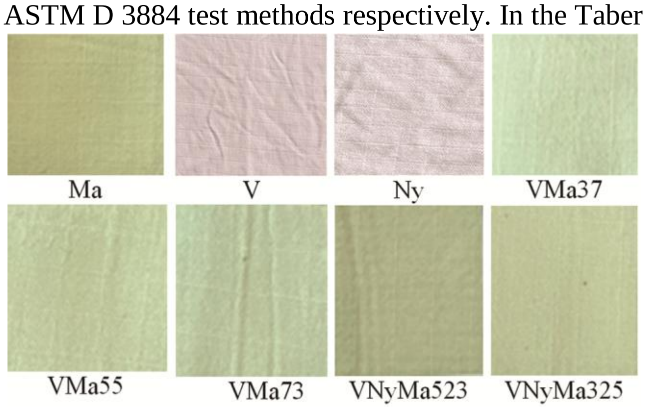

Fig. 1 — Fabric samples

abrasion method, the number of cycles required to break two threads (hole formation) of the fabric, is determined by using CS-10 abrasive wheels and applying 500 g load onto the specimen surface. As per ISO 11612, the minimum requirement of passing workwear fabric is 300 N minimum in both directions and for tear strength, the passing requirement is 10N minimum in both directions

Air permeability of textiles indicates their breathability. The air permeability of fabrics was determined using the WIRA air permeability tester following ISO 9237 test method which indicates the amount of air passing through the test specimen on the scale reading, in terms of cm^3/s/cm^2. ASTM E96 / E96M-16 (upright cup water method) at 32 ±2^{o}C and 50±2% RH with 0.5 - 2.5 m/s air velocity was followed to test water vapour permeability. It was measured on Systester, China**.** The measurements determine how many grams of moisture (water vapour) pass through a square meter of fabric in 24 h. If a fabric represents low vapour permeability it would be unable to pass sufficient perspiration and this could lead to sweat accumulation in the clothing and hence discomfort.

2.3 Thermal Properties

Limiting oxygen index (LOI) was determined using Govmark LOI tester following ISO 4589 test method after conditioning in a standard atmosphere of 65±2 % relative humidity and 27±2^{o}C temperature. LOI is a very important test to know that the fabric is flame retardant or not. In this method, the sample is supported vertically in a transparent chimney, and a mixture of oxygen and nitrogen flows upwards through it. Ten readings of LOI was taken for each sample. The following equation is used to determine the limiting oxygen index (LOI) value of the fabrics:

$$LOI = \frac{[O^2] \times 100}{[O^2] + [N^2]} \qquad ...(1)$$

where [O^2] is the volumetric flow of oxygen in cm^3 /s; and [N^2], the corresponding volumetric flow rate of nitrogen in cm^3 /s (refs 16, 17).

Limited flame spread test was carried out using limited flame spread tester manufactured by Wazau, Germany as per ISO 15025 test standard using two procedures (surface ignition and bottom-edge 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 are recorded.

ISO 12127-1 test method was followed to test contact heat index using WIRA contact heat tester. The threshold time was determined by monitoring the temperature of the calorimeter. The higher the threshold time of a fabric, the better will be the heat-protective property. A heating cylinder was heated to 250° C, maintained at the contact temperature and a test specimen was placed on the calorimeter. The heating cylinder was lowered onto the test specimen supported by the calorimeter or the calorimeter with the specimen was lifted to the heating cylinder. In either case, the operation was carried out at a constant speed. The threshold time was measured by monitoring the temperature of the calorimeter and registered to an accuracy of ± 0.1^0 C.

ISO 6942 B test method was followed to test radiant heat transfer index ($RHTI_{24}$). The fabrics were exposed to a radiant heated source emitting 20 kW/m^2 heat fluxes as per the ISO 11612 standard for clothing to protect heat and flame. The time (s), for the temperature in the calorimeter to rise (24 ± 0.2)^{o}C is recorded. Each sample was tested 10 times for $RHTI_{24}$. The transmitted heat flux density (Q_c) in kW/m^2, was determined using the following equation:

$$Q_c = \frac{M.C_p.12}{A.(t_{24})-(t_{12})} \quad ...(2)$$

where M is the mass of the copper plate in kg; C_p, the specific heat of copper 0.385 kJ/kg ^{0}C; 12/ ($t_{24} - t_{12}$), the mean rate of rising of the calorimeter temperature in ^{0}C/s, in the region between 12^{o}C and 24^{o}C rise; and A, the area of copper plate in m^2.

The heat transmission factor, TF (Q_o), for the incident heat flux density level (Q_o), is given by the following equation :

$$TF\ (Q_o) = Q_c/Q_o \quad ...(3)$$

where Q_c is the transmitted heat flux density.

The convective heat transmission (HTI_{24}) through material is determined as per the ISO 9151 test method. The horizontally oriented test specimen is partially restrained from moving and subjected to an incident heat flux of 80 kW/m^2 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 HTI_{24}.

As per ISO 11612, the requirement for the B1 performance level of $RHTI_{24}$ is 4.0 s to <10 s and for the C1 performance level of HTI_{24}, it is 7.0 s to <20 s. The performance requirement for contact heat is 5.0 s to <10 s for the F1 performance level.

2.4 Statistical Analysis

The experimental data were analyzed using SPSS (version 20). The null hypothesis (H_0) states that there is no relationship between FR viscose: modacrylic fibre blend percentage and limiting oxygen index (LOI), radian heat transfer index ($RHTI_{24}$) and a convective heat transfer index (HTI_{24}) of fabric after 5 washes. An alternative hypothesis states the possibility of a relationship between fibre blend percentage and limiting oxygen index, contact heat index, radiation heat transfer index and a convective heat index of fabric. H_0 is rejected if the p-value is less than the predetermined significance level which is ideally 0.05.

3 Results and Discussion

From Table 3, it is clear that the areal mass of Ma, V, Ny, VMa37, VMa55, VMa73, VNyMa523 and VNyMa325 fabrics are between 174 g/m^2 and 186 g/m^2. The thickness is one of the fabric's basic properties giving information on its warmth, heaviness or stiffness in use. Thickness values of different fabrics are given in Table 3. The further discussion on results is divided into three important requirements of protective textiles. These are durability, comfort and safety. These are discussed below:

3.1 Durability Related Properties

Each fabric is tested for its tensile tear strength and abrasion resistance properties after five and fifty washes. The results are given in Table 3. It shows that Ny (Nylon 66), Ma (Modacrylic) samples are having higher tensile strength (warp-wise 1054 and 641 N and weft-wise 928 to 620 N respectively) than V (FR viscose) fabric. The tensile strength of FR-viscose (warp-wise 485 N and weft-wise 480 N) is found to be the lowest. As all the construction parameters of fabric samples are similar, the change in tensile strength is due to the difference in tenacity of the fibres as well as yarn. Nylon 66 is having higher fibre and yarn tenacity (Tables 1 and 2) than others. This is the reason, its tensile strength is higher than other fabrics. On the other hand, Tables 1 and 2 show that the fibre and yarn tenacity of FR viscose (fibre tenacity 24.21 g/tex, yarn tenacity 12.8 g/tex) is lower

Table 3 — Physical and mechanical properties of fabric

Parameter	Ma	V	Ny	VMa37	VMa55	VMa73	VNyMa523	VNyMa325
Areal density, g/m^2	174	194	204	180	185	186	181	183
Thickness, mm	0.42	0.50	0.51	0.45	0.46	0.44	0.52	0.46
Tensile strength, N (after 5 washes)								
Warp-wise	645	485	1054	638	601	584	505	535
Weft-wise	620	480	928	593	551	499	495	509
Tensile strength, N (after 50 washes)								
Warp-wise	641	410	1062	612	651	582	489	515
Weft-wise	629	398	941	575	600	510	478	490
Tear strength (N) (after 5 washes)								
Warp-wise	22	18	58	29	31	21	30	31
Weft-wise	24	15	48	29	30	20	28	31
Tear strength (N) (after 50 washes)								
Warp-wise	20	12	56	27	30	19	30	30
Weft-wise	21	14	49	28	27	20	27	29
Abrasion resistance (No. of cycles till first hole formation)	157	58	>1000	175	169	167	713	670
Air permeability, cm^3/s/cm^2 at 1.0 kPa foot pressure	15.0	28.1	10.0	19.0	20.2	22.32	16.4	9.0
Water vapour permeability, mg/cm^2/s	8.0	10.0	8.0	9.5	9.7	10.2	8.4	8.2

than other fibres. This may be the reason for the lowest tensile strength of the fabric made out of this fibre. The tensile properties of fabrics mostly depend on the tensile properties of yarns[16]. From Table 2, it is clear that with the increase in FR viscose percentage in the modacrylic and viscose blends (VMa37, VMa55, and VMa73), the tensile strength of the fabric decreases. This may be due to the lower tenacity of FR viscose fibre as compared to modacrylic fibre. The tertiary blends of FR viscose, nylon 66 and modacrylic (VNyMa523 and VnyMa325) show tensile strength of 505 N and 535 N in warp-wise direction and 495 N and 509 N in weft-wise direction. All the fabrics show a little change in tensile strength after 50 washes.

The tear strength of all the fabrics is also tested and the findings are reported in Table 3. It is explicit that the tear strength of Nylon 66 fabric is found to be higher than those of other fabrics, as this is made out of high tenacity yarn. The tear strength of FR viscose fabric is lower than those of other fabrics as it is having the lowest tenacity yarn. The second-lowest tear strength is found to be of VMa73 fabric as it is having 70% of viscose fibre. The modacrylic fabric (Ma) is having 22 N warp-wise and 24 N in weft-wise tear strength. All the binary and tertiary blends show tear strength in the range 28 N - 31 N for both directions.

If the fabric used for FR workwear is not having good abrasion properties, during use, its weight and thickness would reduce, which will ultimately lead to hole formation. Such type of fabric will not fulfil the requirement of workwear of workers working in heat and flame related hazardous environments. Therefore, for such type of workwear, the fabric should have good abrasion properties. It is clear from Table 3 that Ny fabric does not show hole formation even after 1000 Taber abrasion cycles, while Ma and V fabrics get abraded as two threads are broken in 157 and 58 cycles respectively. The higher abrasion resistance of Ny is expected[15]. It is clear from Table 3 that the presence of FR Viscose in the binary blends (VMa37, VMa55, and VMa73) with other fibres affect the abrasion resistance property adversely, because 100% FR viscose fabric (V) is having very poor abrasion resistance. In the case of tertiary blends (VNyMa523 and VNyMa325), the abrasion results are found to be better than those of other fabrics (except Ny fabric). This is because, these tertiary blends contain nylon 66 fibres, which has good abrasion resistance properties.

3.2 Comfort Related Properties

Many properties of fabric can affect its comfort characteristics. Air permeability and water vapour permeability are the two important properties. As per the results presented in Table 3, 100% FR viscose fabric shows the highest air permeability (28.1 cc/s/cm^2), while 100% Nylon 66 shows the lowest (10 cc/s/cm^2) air permeability. Modacrylic fabric (Ma) shows 15 cc/s/cm^2 air permeability. The air permeability of fabric is affected by many factors, such as fibre fineness, structural properties (shape and value of pores of the fabric), and the yarn and fabric thickness[18-21]. Earlier studies[15] have shown that FR viscose fabric is having good air permeability. The air permeabilities of VMa37, VMa55, and VMa73 are also found to be better as compared to other fabrics except for FR viscose as these binary blends are having viscose components in their blends.

Water vapour permeability is a property of fabric that indicates its ability to allow vapour to pass through it under a given set of conditions. The higher the value of the water vapour permeability of the fabric, the more rapidly vapour can pass through it. Water vapour permeability values of V fabric and all the binary blends of FR viscose (VMa37, VMa55 andVMa73 are found high (9.5 mg/cm^2/s, 9.7 mg/cm^2/s, and 10.2 mg/cm^2/s respectively) as compared to other fabrics (Table 3). Ma and Ny fabrics show the same water vapour permeability. Both the tertiary blends (VNyMa523 and VNyMa325) show better water vapour permeability as compared to M1 and Ny fabrics, as they are having FR viscose fibre as one of the components.

3.3 Safety-related Properties

Fabric flammability behaviour is an important issue, which is directly linked to the safety of wearer, especially working in a fire hazardous environment like foundries, oil and gas industry, hotel kitchens, fire stations, etc. Flame-retardant clothing not only reduces burn injury but also provides escape time and increases the chances of survival. Hence, it is important to test the fabrics to evaluate their heat and flame properties like limiting oxygen index, contact heat index, radiation heat transfer index and convective heat index.

3.3.1 Limited Flame Spread

The results of the limited flame spread test (surface ignition and bottom-edge ignition) of vertically oriented samples are given in Table 4. It is observed that all the samples, except Ny (Nylon 66), meet the requirement of ISO 11612 after 5 and 50 washes. As per ISO 11612, the flame shall not reach the upper and side edges of any specimens, there shall not be any flaming debris, no hole formation, and afterglow and afterflame time shall be $\leq$ 2s. Nylon 66 fabric meets only the afterglow requirement. It failed to meet other requirements[22].

3.3.2 Limiting Oxygen Index (LOI)

Table 5 shows that the LOI of modacrylic (Ma) and FR-viscose (V) are 33%, and 26.5% respectively after five washes as compared to Nylon 6, 6 (Ny), which is having 21%. There is very little change in LOI after 50 washes of these fibres. On the other hand, VMa37, VMa55, and VMa73 fabrics are having 30%, 28%, 27.5% LOI respectively after 50 washes. VMa37 is having a higher LOI, as it contains a higher percentage of modacrylic fibres. Modacrylic is having a higher LOI as compared to FR viscose. In the case of tertiary blends, the LOI is found to be lower than the binary blends due to the presence of Nylon 66 fibres in the tertiary blends. Nylon 66 is having the lowest LOI as compared to other fibres. Not much difference is recorded in LOI after 50 washes. The standard deviations of LOI values of all the samples are also given in Table 5. The value of standard deviation is on the lower side which indicates reproducibility of results. A comparative graph between LOI and different fabrics after 5 and 50washes are given in Fig. 2. This also indicates that there is no significant change in LOI value after 5 and

Table 4 — Limited flame spread test- surface and edge ignition

Property	Ma	V	Ny	VMa37	VMa55	VMa73	VMaNy523	VMaNy325
Flame reaches top edge or either side edge								
After 5 washes								
- Surface ignition	No	No	Yes	No	No	No	No	No
- Edge ignition	No	No	Yes	No	No	No	No	No
After 50 washes								
- Surface ignition	No	No	Yes	No	No	No	No	No
- Edge ignition	No	No	Yes	No	No	No	No	No
Hole develop (Only for surface ignition)								
After 5 washes	No	No	Yes	No	No	No	No	No
After 50 washes	No	No	Yes	No	No	No	No	No
Occurrence of flaming debris								
After 5 washes								
- Surface ignition	No	No	Yes	No	No	No	No	No
- Edge ignition	No	No	Yes	No	No	No	No	No
After 50 washes								
- Surface ignition	No	No	Yes	No	No	No	No	No
- Edge ignition	No	No	Yes	No	No	No	No	No
After flame time, s								
After 5 washes								
- Surface ignition	Nil	Nil	25	Nil	Nil	Nil	Nil	Nil
- Edge ignition	Nil	Nil	21	Nil	Nil	Nil	Nil	Nil
After 50 washes								
- Surface ignition	Nil	Nil	66	Nil	Nil	Nil	Nil	Nil
- Edge ignition	Nil	Nil	61	Nil	Nil	Nil	Nil	Nil
After glow time, s								
After 5 washes								
- Surface ignition	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
- Edge ignition	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
After 50 washes								
- Surface ignition	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
- Edge ignition	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

50 washes. It is a well-known fact that fibres having LOI values of 21% or below ignite easily and burn rapidly in the air (around 21% oxygen). On the other hand, fibres with LOI values above 21% ignite and burn slowly. Generally, fibres having LOI values above 26% may be considered as a flame retardant[23].

3.3.3 Contact Heat Index

The contact heat transmission test method is used to test protective clothing (including hand protectors like gloves) and its constituent materials intended to protect against high contact temperatures. The threshold time is determined by monitoring the temperature of the calorimeter. Higher the threshold time of fabric, better will be the heat-protective property. It is clear from Table 5, Nylon 66 (Ny) is having the lowest threshold time as compared to others. The other fabrics are having a threshold time of around 5 s after 5 washes. These samples meet the F1 performance level of contact heat as mentioned in ISO 11612. No remarkable change is seen after 50 washes in the contact heat index of all the fabrics. The standard deviations of contact heat index values of all the samples are also given in Table 5. The value of standard deviation is on the lower side, which indicates reproducibility of results.

3.3.4 Radiant Heat Transfer Index

Radiant heat transfer index ($RHTI_{24}$) is studied to determine the behaviour of fabric for heat-protective clothing when subjected to heat radiation. Under this method, fabrics are exposed to a radiant heat source emitting 20 kW/m^2 heat fluxes. Higher the time taken to raise the temperature of the calorimeter to $(24\pm0.2)^oC$, the better will be the fabric in radiant heat resistance point of view. It is clear from Table 5 that Modacrylic (Ma) is having a higher $RHTI_{24}$ (12.9 s) as compared to 100 % FR viscose (V), which is

Table 5 — Flame-retardant properties

Test parameter	Ma	V	Ny	VMa37	VMa55	VMa73	VMaNy523	VMaNy325
Limiting oxygen index, %								
After 5 washes	33.0 (0.81)	26.5 (0.78)	21.0 (0.87)	30.0 (0.92)	29.5 (0.85)	27.0 (0.79)	23.5 (0.80)	23.5 (0.82)
After 50 washes	33.5 (0.78)	27.0 (0.82)	21.0 (0.72)	30.0 (0.92)	28.0 (0.86)	27.5 (0.84)	23.0 (0.90)	24.0 (0.84)
Contact heat index, s								
After 5 washes	5 (1.0)	5 (1.0)	4 (0.0)	5 (1.0)	5 (1.0)	5 (0.0)	5 (0.0)	5 (1.0)
After 50 washes	6 (0.0)	5 (0.0)	5 (1.0)	5 (1.0)	5 (0.0)	5 (0.0)	5 (1.0)	5 (0.0)
Radiant heat transfer index ($RHTI_{24}$), s								
After 5 washes	12.9 (0.76)	12.1 (0.88)	12.2 (0.87)	12.6 (0.89)	12.4 (0.88)	12.2 (0.84)	13.6 (0.93)	12.6 (0.89)
After 50 washes	12.9 (0.86)	12.0 (0.70)	12.0 (0.72)	12.4 (0.96)	12.0 (0.82)	12.3 (0.76)	13.5 (0.88)	12.5 (0.76)
Convective heat transfer index, (HTI_{24}), s								
After 5 washes	5.0 (0.1)	6.2 (0.2)	3.7 (0.3)	5.2 (0.2)	5.5 (0.3)	5.7 (0.1)	5.0 (0.3)	5.3 (0.1)
After 50 washes	5.0 (0.2)	6.1 (0.1)	3.5 (0.4)	5.0 (0.2)	5.4 (0.1)	5.6 (0.2)	5.3 (0.3)	5.0 (0.1)

Values in brackets are standard deviations.

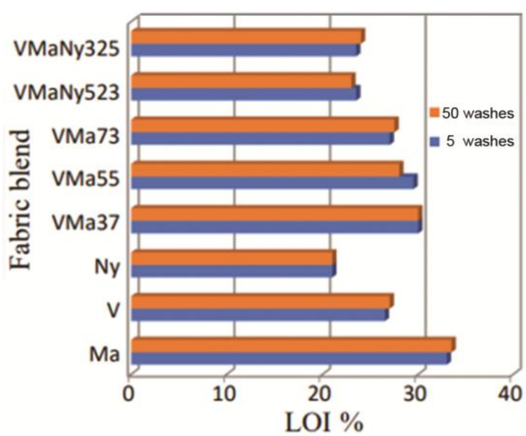

Fig. 2 — Limiting oxygen index of fabric samples

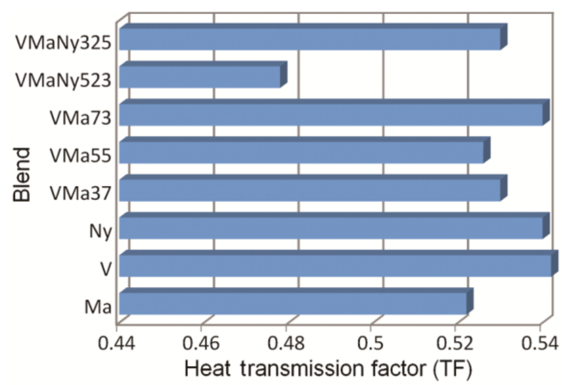

Fig. 3 — Heat transmission factor of fabric samples after 5 washes

having 12.1 s. Nylon 66 is having 12.2 s $RHTI_{24}$. On the other hand, binary blends of VMa37, VMa55 and VMa73 are having 12.6 s, 12.4 s and 12.2 s $RHTI_{24}$ respectively. The tertiary blends VNyMa523 (13.6 s) and VNyM325 (12.6 s) exhibit better $RHTI_{24}$ as compared to 100 % FR viscose and Nylon 66 after 5 washes. After 50 washes, all the fabrics have shown almost nil changes in $RHTI_{24}$. All the samples meet the performance level C1 of the radiant heat transfer factor as per ISO 11612. The standard deviations of $RHTI_{24}$ values of all the samples are also given in Table 5. The value of standard deviation is on the lower side which indicates the reproducibility of results. The heat transmission factor (TF) for the incident heat flux density level Q_o, after 5 washes of all the samples is also determined and shown in Fig. 3. It is clear that the sample VMaNy523 is having the lowest value of heat transmission factor, which indicates that this fabric is having properties better than other fabrics to protect the wearer from radiant heat exposure.

3.3.5 Convective Heat Index

The results of the convective heat index (HTI_{24}) are shown in Table 5. It is clear that V fabric shows 6.2 s

Table 6 — Multivariate test analysis among blend ratio of fibre blend and LOI, $RHTI_{24}$ and HTI_{24}

Source	Dependent variable	Type III sum of squares	df	Mean square	F	Sig. (p)
Corrected Model	LOI	286.506[a]	6	47.751	256.053	0.000
	$RHTI_{24}$	7.422[b]	6	1.237	36.748	0.000
	HTI_{24}	9.002[c]	6	1.500	131.124	0.000
Intercept	LOI	27988.716	1	27988.716	150082.902	0.000
	$RHTI_{24}$	5272.419	1	5272.419	156624.550	0.000
	HTI_{24}	1097.600	1	1097.600	95928.455	0.000
BLEND	LOI	286.506	6	47.751	256.053	0.000
	$RHTI_{24}$	7.422	6	1.237	36.748	0.000
	HTI_{24}	9.002	6	1.500	131.124	0.000
Error	LOI	8.019	43	0.186		
	$RHTI_{24}$	1.447	43	0.034		
	HTI_{24}	0.492	43	0.011		
Total	LOI	42257.570	50			
	$RHTI_{24}$	7694.390	50			
	HTI_{24}	1457.790	50			
Corrected total	LOI	294.525	49			
	$RHTI_{24}$	8.870	49			
	HTI_{24}	9.494	49			

[a] R Squared = 0.973 (Adjusted R Squared = .969).
[b] R Squared = 0.837 (Adjusted R Squared = .814).
[c] R Squared = 0.948 (Adjusted R Squared = .941).

HTI_{24}, which is highest than in other fabrics. Ny fabric shows 3.7 s HTI_{24} value, the lowest amongst all fabrics after 5 washes. The other fabrics are showing HTI_{24} values between 5.0 s and 5.3 s. After 50 washes, there is no significant change in HTI_{24} values of all fabrics. All the samples except Ny, meet the performance level B1 of the convective heat transfer factor as per ISO 11612. The standard deviations of HTI_{24} values of all the samples are also given in Table 5. The value of standard deviation is on the lower side, which indicates reproducibility of results.

3.4 Statistical Analyses

Table 6 shows the results of the multivariate test analysis, which is applied to find out the effect of fibre blend ratio of FR viscose and Modacrylic limiting oxygen index (LOI), radiation heat transfer index ($RHTI_{24}$)and a convective heat index (HTI_{24}) of fabric after 5 washes. The null hypothesis (Ho) is rejected as the p-value is less than a pre-determined significance level (0.05). The result indicates that there is a relationship between fibre content in the blend and heat and flame properties.

The regression coefficient (R^2) value is 0.973, 0.837 and 0.948, which indicates a very strong relationship between the FR viscose: modacrylic blends and LOI, $RHTI_2$4 and HTI_{24}

4 Conclusion

In this study, the effect of different contents of modacrylic fibres in various fibres blended fabric on thermal, comfort and mechanical properties has been studied. The applications of these blends are explored for the workwear of oil & gas industry workers, which followed ISO 11612 standard. The following conclusions are drawn:

4.1 All the fabrics are having the same constructional particular with areal density varies from 174 g/m^2 and 186g/m^2. Nylon 66 and modacrylic fibres blended fabrics show higher tensile and tear strengths. These mechanical properties are meeting the requirements of international standards on workwear ISO 11612. The Taber abrasion of Nylon 66 blended fabric is found to be higher as compared to without nylon 66 blended fabric. FR viscose fabric (coded as V) is having the lowest abrasion resistance.

4.2 FR viscose fabric (coded as V) shows the highest air and water vapour permeability. The binary blends of FR viscose with modacrylic (VMa37, VMa55, and VMa73) show the second highest values of air and water permeability as compared to other fabrics, indicating that the presence of FR viscose improves the comfort properties of the fabric.

4.3 The limiting oxygen index is a preliminary test to evaluate the flame resistance property of the fabric. Except for Ny, VNyMa523, and VNyMa325, all fabrics are flame retardant and have an LOI of more than 26%. The lower LOI of tertiary blends may be due to the lower LOI of Nylon 66 fibre, as all these tertiary blends contain Nylon 66.

4.4 All the samples, except Ny, meet the requirement of limited flame spread test (surface ignition and bottom edge ignition) as per ISO 11612.

4.5 The contact heat of all the fabric except Ny is found to be similar and met the minimum requirement of ISO 11612.

4.6 The radiant heat transfer index ($RHTI_{24}$) of the fabric coded as Ma (Modacrylic) is higher than others. The FR viscose fabric (V) and Nylon 66 fabric (Ny) are having almost similar $RHTI_{24.}$ There is not much change observed in the binary and tertiary blends of modacrylic except VMaNY523, which is showing $RHTI_{24}$ vlaue of 13.6 s after 5 washes. All these samples are meeting the requirement of ISO 11612.

4.7 The heat transfer index (HTI_{24}) values of FR viscose (V) is found to be the highest (6.2 s) among all fabrics. Modacrylic (Ma) fabric is showing the second-highest value (5.0 s) of HTI_{24}. The fabric coded as Ny is having the lowest HTI_{24} value, which is 3.7 s. The binary blends VMa37, VMa55 and VMa73 are showing HTI_{24} value from 5.2 s to 5.7 s. The HTI_{24}value of VNyMa523, and VNyMa325 are 5 s and 5.3 s respectively. All the samples except Ny, meet the performance level B1 of the convective heat transfer factor as per ISO 11612.

4.8 There is not much difference in properties related to thermal after 5 and 50 washes. The FR viscose and modacrylic fibres are inherently flame retardant and therefore after washing their thermal properties are not affected.

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