

# Fire-resistant and thermo-physiological comfort properties of balaclava for firefighter clothing

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Balaclavas are essential protective clothing in firefighting, and their thermo-physiological comfort properties are critical for ensuring wearer safety and performance. This research aims to enhance the flame resistance of firefighter balaclava materials through innovative design and material selection, striving for superior protection and comfort in high-temperature environments. Twenty-seven fabric combinations, varying in density and layering, are evaluated using para-aramid, meta-aramid, and a cotton blend as the control. Several configurations exceed standard protection thresholds, enabling safe operation under extreme heat without compromising comfort. The relative contributions of fibre type, fabric density, and layering are analysed using statistical methods to assess their effects on thermal resistance, conductivity, and heat transfer modes (contact, radiant, and convective). Results indicate that meta-aramid fabric with areal densities of 400 g/m<sup>2</sup> (for 1-3 layered fabrics) and 250 g/m<sup>2</sup> (for 2- and 3-layered fabrics) provide optimal protection, as they swell under heat exposure to create an additional barrier. Para-aramid fabrics perform effectively across all three-layered configurations, offering high thermal stability, strength, and resistance to shrinkage. The findings provide material-specific recommendations for designing advanced firefighter balaclavas with improved protective and comfort characteristics.

**Keywords:** Aramid fibre, Balaclava, Flame resistance, Heat transfer, Layering effect, Thermal performance

## 1 Introduction

Firefighting is an occupation that involves hazardous environments and requires intense physical work, making it one of the most dangerous jobs. To ensure their safety, firefighters must wear protective gear, including a turnout ensemble (coat and pants)<sup>1</sup>, and other personal protective equipment (PPE), that meets the National Fire Protection Association (NFPA) 1971-81 standards<sup>2</sup>. Before selecting clothing materials, these standard requirements must be considered. Aramid fibres, particularly meta-aramid, are the most common due to their high heat resistance, non-ignitability, and non-melting properties<sup>3</sup>. The Fluorescent Aerosol Screening Test (FAST) demonstrated that particulate infiltration was significant around the head and neck, leading to the requirement of protective balaclavas by NFPA under firefighters' helmets<sup>4</sup>. The extant literature suggests various fibres, including Flame-Resistant Rayon

(Lenzing FR®), Polybenzimidazole (PBI®), Polyimide (P84®), Meta-Aramid (Nomex®), Para-Aramid (Kevlar®) and Carbon fibre (Carbon Shield™) to improve the fire resistance properties of fabrics<sup>5,6</sup>. Inherently fire-retardant fibres are a promising alternative to using FR additives on fabrics, but they often lack comfort properties. Increasing the number of layers of FR material in a balaclava enhances protection. However, it is not a straightforward solution due to various conflicting considerations. A thick or multi-layered balaclava may not fit properly into standard helmets, potentially causing communication issues and necessitating expensive custom sizing. Instead, when wearing a helmet, a two-layered hood (as illustrated in Fig. 1)<sup>7</sup> is recommended for better compatibility.

The study evaluates the effectiveness of fire balaclavas, which are integral components of fire-protective clothing. According to the NFPA 1971 standard, fire-protective clothing, including balaclavas, must meet specific requirements such as flame resistance, air permeability, thermal resistance, heat

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Fig. 1 — Firefighter helmet with Balaclava<sup>5</sup>

transfer, high limiting oxygen index, low toxicity of gases, the ability to withstand high temperatures without melting, and low moisture absorption<sup>3,5</sup>. However, Nomex, a type of meta-aramid, may shrink under intense heat. To address this, para-aramid (Kevlar®) is often blended with Nomex® to reduce heat shrinkage, resulting in blends like Nomex IIIA (93 % Nomex, 5 % Kevlar, and 2 % antistatic fibre). Para-aramid fibres offer superior tensile strength (2.5 times that of nylon), elasticity, impact resistance, fatigue resistance, heat resistance, and chemical resistance. Additionally, Nomex® fibres have the advantage of swelling and thickening when exposed to flames, creating a protective barrier that stays cool and provides extra seconds of protection.

This research aims to investigate the thermal protective performance and comfort of balaclavas and their materials focusing on improving both safety and comfort for firefighters. Despite its pivotal role in shielding vulnerable areas of the head and neck, the protective balaclava often goes unnoticed<sup>3</sup>. It plays a significant role in protecting firefighters from minute particulate matter, such as soot and smoke, which can infiltrate structural firefighting ensembles and potentially increase cancer rates among firefighters. Statistical tools were employed to determine the optimal layering and areal density (grams per square meter) to enhance comfort while maintaining fire resistance.

## 2 Materials and Methods

### 2.1 Materials

Three types of yarn were used in this study: 100 % para-aramid, a 93/5/2 % blend of meta-aramid/para-aramid/antistatic yarn, and an 83/17 % cotton/polyester yarn, the latter serving as a control sample. These yarns had counts of 21/1, 20/1, and 21/1 Tex respectively. These yarns were directly sourced from High-Performance Textile Pvt. Ltd., Panipat, Haryana, India. Ring-spun yarns were produced using

the ring-spinning process, which enhanced yarn strength and reduced shrinkage in para-aramid fibres. The antistatic properties in the meta-aramid blend made the yarns less likely to ignite and spread fire. The cotton yarn, used as a control, exhibited thermal conductivity of approximately 0.035 W/m·K. It was selected for its inherent ability to retain warmth, soft and snug fit, moisture absorption, breathability, and excellent heat resistance performance up to 110 °C. All other samples were compared against the control to evaluate their performance.

### 2.2 Fabrication of Fire-Resistant Fabric

All samples were produced using a rib-knitted structure [Fig. 2 (a)-(e)] on a 12-gauge knitting machine (HPT Industry, Panipat, India). Consistent knitting parameters, such as stitch length, stitch density, tightness factor, and input tension, were maintained across all samples. Different fibres and areal density (grams per square meter) measurements were used to examine fabric variations, as detailed in Table 1. The performance of the fabric was evaluated at different GSM levels under single-, double-, and triple-layer configurations.

### 2.3 Characterisation and Measurement Techniques

All samples were conditioned for 24 h in a standard testing environment ( $20 \pm 2$  °C,  $65 \pm 2\%$  RH) before characterisation. Standard test methods and calibrated laboratory equipment were used. Fabric thickness was determined with a digital fabric thickness tester following ASTM-D-1777 standard. The course and wale densities were assessed using a magnifying pick glass. Areal density ( $\text{g/m}^2$ ) was measured using a GSM cutter in accordance with ASTM D3776<sup>11</sup>.

#### 2.3.1 Air Permeability

Air permeability was evaluated using an SDL ATLAS model M021A in accordance with ASTM D-737-96<sup>12</sup> and ISO 9237:1995<sup>15</sup> standards. Measurements were carried out at 125 Pa, where air was drawn through the specimen and the airflow was recorded with a flowmeter.

#### 2.3.2 Thermal Properties

The thermal characteristics of the materials were tested using the Alambeta instrument as per the standard procedure ASTM C518 [Fig. 3 (a)]. The instrument was used to evaluate thermal resistance, thermal conductivity, thermal absorptivity, thermal diffusivity, and total heat loss tests.<sup>12</sup>

#### 2.3.3 Contact Heat Transmission

Contact heat transmission was assessed using ISO 12127<sup>13</sup> (T424 ITT) [Fig. 3 (c)]. The mean threshold

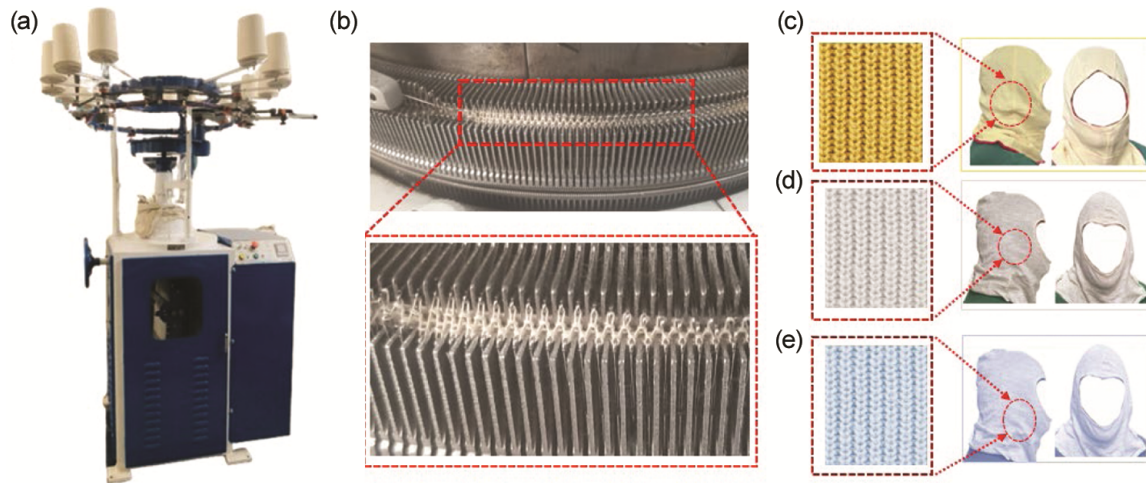


Fig. 2 — Design and fabrication of fire-resistant protective textiles in the form of balaclava: (a) knitting machine, (b) loop arrangement on the machine and schematic representation during knitting, and optical images of balaclavas made of (c) para-aramid, (d) meta-aramid, and (e) cotton

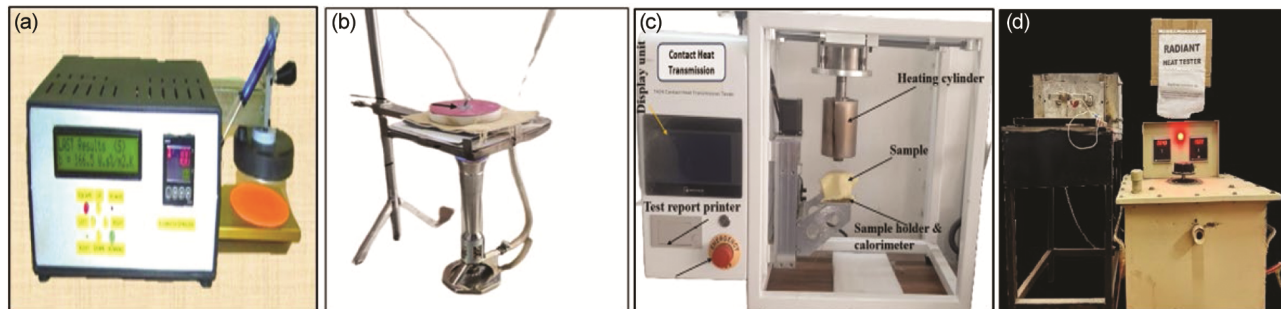


Fig. 3 — (a) Alambeta thermal tester, (b) convective heat transmission testing instrument, (c) contact heat transmission testing instrument and (d) radiant heat transmission testing instrument

Table 1 — Physical properties of knitted fabric samples

Properties	Para-aramid fabric			Meta-aramid fabric			Cotton fabric		
	150	250	400	150	250	400	150	250	400
Areal density, GSM	150	250	400	150	250	400	150	250	400
Thickness, mm	0.50	0.90	1.39	0.50	1.05	1.45	0.65	1.05	1.40
Courses per inch	16	10	8	17	8	7	18	9	7
Wales per inch	39	24	22	38	22	20	39	22	20
Loop length, cm	0.19	0.73	0.82	0.21	0.69	0.78	0.20	0.70	0.80

time was determined at heating cylinder temperatures of 100 °C, 200 °C, and 250 °C. Threshold time was defined as the duration (s) required to raise the calorimeter temperature by 10 °C above ambient. For proximity fire-fighter clothing (PFFC) and structural fire-fighter clothing (SFFC), a threshold time  $\geq 10$  s at 250 °C was required.

#### 2.3.4 Heat and Thermal Shrinkage Resistance

Heat resistance and thermal shrinkage were evaluated in a forced hot air oven following ISO 17493<sup>12</sup> standard. Samples were exposed to  $(185 \pm 5)$  °C or  $(260 \pm 5)$  °C for at least 5 min. The NFPA 1971 Protective Hood Requirement limits shrinkage to 10 %<sup>13</sup>.

#### 2.3.5 Flammability Test

ASTM D-6413 was used to test the fire resistance of textiles. The test measured burning behaviour, char length, after-flame, and after-glow time under controlled lab conditions. The specimens were prepared in a standard size, and a flame of 3.9 cm was applied for 12 s. The char length requirement for bottom ignition was 100 mm maximum<sup>14</sup>.

#### 2.3.6 Radiant Heat Transmission

Radiant heat resistance was measured using ISO 6942:2022 [Fig. 3 (d)]. The samples were exposed to a radiant heat flux of 20 kW/m<sup>2</sup> (as per requirement). The heat transfer index (HTI<sub>20</sub>) was determined as the

time required for a 20 °C temperature rise, which was required to exceed 20 s<sup>15</sup>.

### 2.3.7 Convective Heat Transmission

Convective heat resistance was tested using ISO 9151 [Fig. 3 (b)]. Three fabric specimens (14 × 14 cm) were placed 50 ± 2 mm from an 80 ± 2 kW/m<sup>2</sup> calibrated burner. Contact temperature and threshold time were recorded using a calorimeter. Accurate contact temperature and threshold time recording is vital for safety and efficacy<sup>16</sup>.

### 2.3.8 Statistical Analysis

A full factorial design was employed to investigate the effect of fibre type (cotton, para-aramid, and meta-aramid), GSM (150, 250, and 400), and layering (single, double, and triple layer) on fabric performance.

## 3 Results and Discussion

### 3.1 Flammability Test

Flammability testing is carried out on all fabric samples in accordance with ASTM D 6413-08, which specifies the requirements for firefighter clothing materials, seams, and face and bottom ignition. To meet the requirements, the top and sides of the specimen must remain free of fire, with no holes or molten/flaming particles, while the after-flame/after-glow period is restricted to an average of 2 s. In addition, the bottom ignition should have a maximum char length of 100 mm, and burning should have a maximum 5 mm hole formation, excluding non-flame protection interlinings.

Table 2 presents the visual assessment of para-aramid (PA), meta-aramid (MA), and cotton fabrics during flammability testing. Each sample is exposed to a flame for 12 s. The results indicate that PA-150 ignites within 12 s, while PA-250 demonstrates better flame resistance, and PA-400 shows no ignition under the same conditions. Meta-aramid samples, however, exhibit greater susceptibility to heat due to shrinkage, which concentrates the flame impact and increases localised damage. The effect is most pronounced in MA-150, while MA-250 and MA-400 show improved performance but remain less effective than para-aramid fabrics at the same areal density. The cotton control sample fails under direct flame exposure, burning completely, although it performs satisfactorily in other thermal protection tests.

The difference in performance is attributed to the higher thermal decomposition temperature of para-aramid fibres, resulting from stronger intermolecular forces compared with meta-aramid. This makes para-

aramids more suitable for high-performance fire-resistant applications.

The limiting oxygen index (LOI) further supports these findings. LOI is a crucial metric for measuring the flame resistance of a material. It indicates the minimum concentration of oxygen in the atmosphere required to support combustion of the material. Fibres with an LOI greater than 25 are considered flame resistant, meaning that at least 25 % oxygen must be present for them to burn. Higher LOI values signify a material's increased difficulty in catching fire. Para-aramid fibres exhibit an LOI of 29 and meta-aramid fibres an LOI of 28–30, both well above the threshold of 25, confirming excellent flame resistance. These properties reinforce the suitability of aramid-based fabrics in protective firefighter clothing, particularly balaclavas<sup>17</sup>.

### 3.2 Air Permeability

Air permeability significantly impacts the comfort of a fabric, with para-aramid and meta-aramid fabrics becoming less air-permeable as their weight and layering increase. While fabrics with higher areal density and multiple layers offer better thermal protection, they provide lower air-permeability and may fit tighter, which can be problematic under the NFPA guidelines.






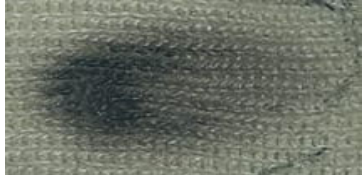

As observed in Fig. 4 (a), samples with a density of 400 GSM and 2-3 layers of para-aramid and meta-aramid provide superior thermal protection due to low porosity and air permeability. However, these fabrics may not meet comfort standards due to their tight fit.

ANOVA results (Table 3) show that fabric density has the greatest influence on air permeability (46.80 %), followed by layering (37.05 %), while fibre type contributes only 3.53 %. The two-way ANOVA results for air permeability also highlight significant F-values for these factors, confirming their impact. The analysis reveals that layering has the greatest impact on the air permeability performance of the balaclava. Interactions between factors have a minimal contribution to air permeability. The high contribution of fabric areal density indicates its significant effect on breathability and physical comfort. In contrast, the lesser contribution of fibre type suggests it has a smaller impact on breathability and physical comfort.

### 3.3 Thermal Properties

Thermal resistance and conductivity are critical for assessing insulation performance (Fig. 4 (b)). Meta-aramid fabric offers the highest thermal resistance

Table 2 — Visual analysis of Para-Aramid (PA), Meta-Aramid (MA) and cotton fabrics during flammability test

Sample	Char length, cm	After-glow time, s	After-flame time, s	Burnt sample image
PA-150	2.5	0	2	
PA-250	1.5	0	1	
PA-400	0.8	0	0	
MA-150	3.4	0	0	
MA-250	2.1	0	0	
MA-400	1.2	0	0	
Cotton (control)	burn	burn	burn	

(0.13), while para-aramid fabric has a lower resistance (0.09) due to its higher thermal conductivity (0.07). Both cotton and para-aramid fabrics exhibit higher conductivity than meta-aramid fabrics, affecting their insulation effectiveness, as lower thermal conductivity values indicate a better ability to resist heat transfer. Cotton insulation, with a typical thermal conductivity of approximately 0.035 W/m·K, provides advantages such as effective warmth retention, a soft and snug fit, moisture absorption, and breathability.

Thermal heat loss (THL) and thermal protective performance (TPP), tested in accordance with ASTM F-1868, confirm that all fabric combinations exceed the NFPA minimum requirement of 205 W/m<sup>2</sup>. The increase in thermal resistance is attributed to the fibres' aromatic or ladder-like chain structures, with meta-aramid having a more linear and aromatic fibre structure.

ANOVA analysis (Table 3) indicates that layering contributes the most to thermal resistance (64.82 %),

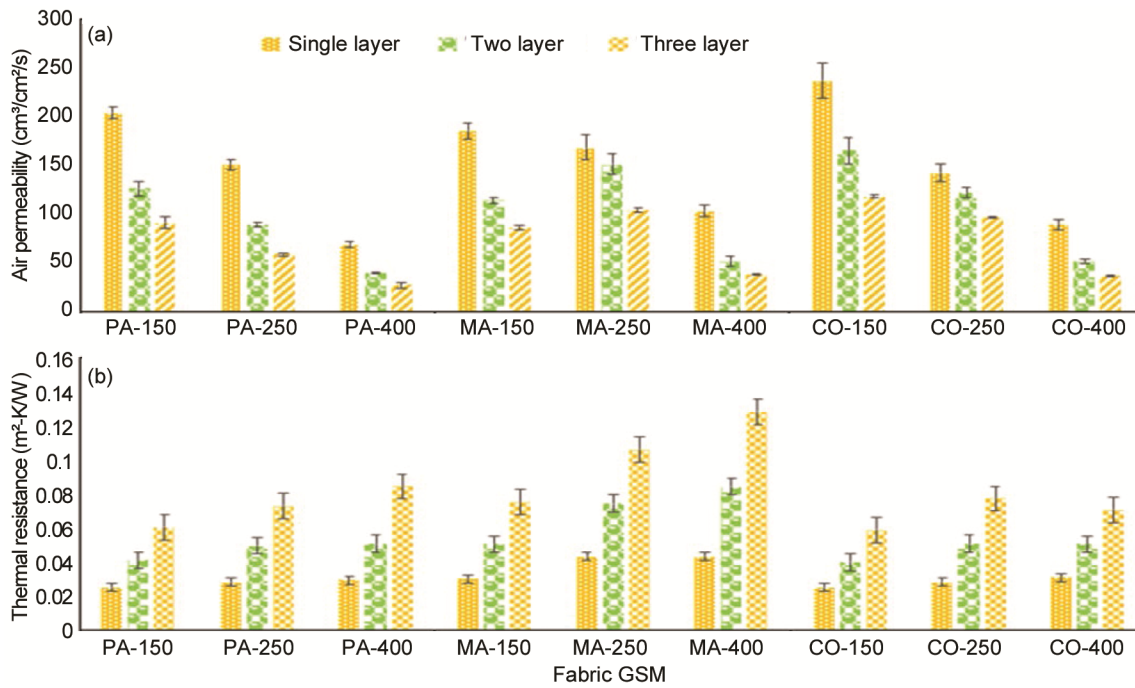


Fig. 4 — (a) Air permeability and (b) thermal resistance of different fabric combinations

Table 3 — Contribution (%) of parameters to thermo-physiological comfort properties during heat exposure

Parameters	Percentage contribution		
	Air permeability, Unit	Thermal resistance, Unit	Thermal conductivity, Unit
Fibre type	3.53	16.64	27.30
Fabric areal density, GSM	46.80	9.53	50.41
Layering	37.05	64.82	14.42
Fibre type vs GSM	7.51	3.04	5.98
Fibre type vs layering	--	2.72	--
Layering vs GSM	--	--	--

‘--’ indicates the non-significance at a 5 % level and negligible % of the contribution.

followed by fibre type (16.64 %), and the interaction between fibre type and GSM (3.04 %). Layering is significant only in the 3-way ANOVA analysis, not the 2-way analysis. For thermal conductivity, fabric density has the highest impact (50.41 %), followed by fibre type (27.30 %). Interactions, such as fibre type × GSM (5.98 %), also play a significant role.

It has been observed that fabric layering significantly impacts thermal resistance more than other factors. The type of fabric has a minimal effect on thermal resistance, although an interaction effect between fibre type and fabric density is noted. Similarly, fabric density has a more substantial impact on thermal conductivity compared to other factors. The type of fabric has a minor effect on thermal conductivity, but an interaction effect between fibre types and fabric density is evident.

### 3.4 Contact Heat Transfer

Contact heat transfer performance is shown in Fig. 5. The duration for heat penetration through the fabric increases with both fabric density and layering. At 250 °C, meta-aramid provides superior protection compared to para-aramid and cotton, due to its unique property of swelling and thickening, which creates a protective barrier against the heat source, offering additional seconds of protection. However, cotton outperforms para-aramid at temperatures of 100 °C, 200 °C, and 250 °C, due to its excellent heat resistance, as shown in Fig. 5. Cotton could perform better in certain scenarios at lower temperatures due to its natural ability to handle thermal insulation or heat absorption. Cotton initially performs better at lower temperatures due to its moisture content, which can provide additional heat resistance by absorbing heat energy before it starts to degrade.

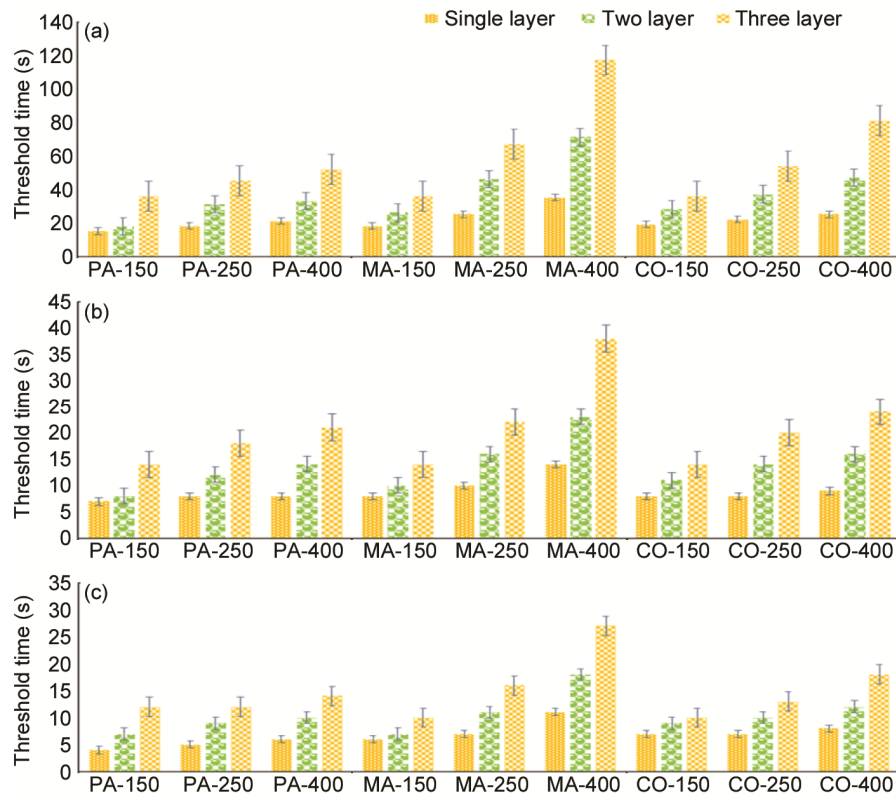


Fig. 5 — Contact heat transfer of different fabric combinations (a) 100 °C, (b) 200 °C, and (c) 250 °C

Table 4 — Contribution, % of different parameters on contact heat transmission of the balaclava during Heat exposure

Parameter	Contribution, %		
	100 °C	200 °C	250 °C
Fibre type	11.81	9.35	10.36
Fabric density, GSM	24.99	23.52	24.89
Layering	42.66	49.02	42.99
Fibre type vs GSM	7.36	7.52	10.37
Fibre type vs layering	--	--	--
Layering vs GSM	7.87	7.31	6.31

'--' indicates the non-significance at a 5 % level and negligible % of the contribution.

ISO 12127-1 requires minimum threshold time of 15 s at 200 °C and 10 s at 250 °C for contact heat tests. Only a select few fabrics meet the required criteria, such as para-aramid fabric with densities of 250 and 400 GSM and three layers. Additionally, meta-aramid fabric with 250 and 400 GSM densities across single, double, and triple layers also meets the criteria.

ANOVA results (Table 4) reveal that layering contributes most to contact heat protection (42.66 %), followed by fabric density (24.99 %) and fibre type (9.35 %). Significant interaction effects are observed between fibre type × GSM and layering × GSM. These results highlight the importance of layering and density in enhancing protection against contact heat in firefighter balaclavas.

Furthermore, the heat and thermal shrinkage test, conducted to assess sample tolerance to high temperatures, reveals that none of the samples exhibit shrinkage beyond 10 % when exposed to hot air at 185 °C, meeting the NFPA 1971 protective hood requirement.

### 3.5 Radiant Heat Transfer Index (RHTI)

The multilayer clothing assembly exhibits a heat flux density of 20 kW/m<sup>2</sup>, meeting the standards for outdoor firefighting work (mean RHTI<sub>20</sub> ≥ 10 s) and firefighting apparel for structural fire risks (mean RHTI<sub>20</sub> ≥ 20 s). Fig. 6(a) shows that multilayer aramid fabrics provide superior radiant heat protection, particularly at higher GSM levels. Two-

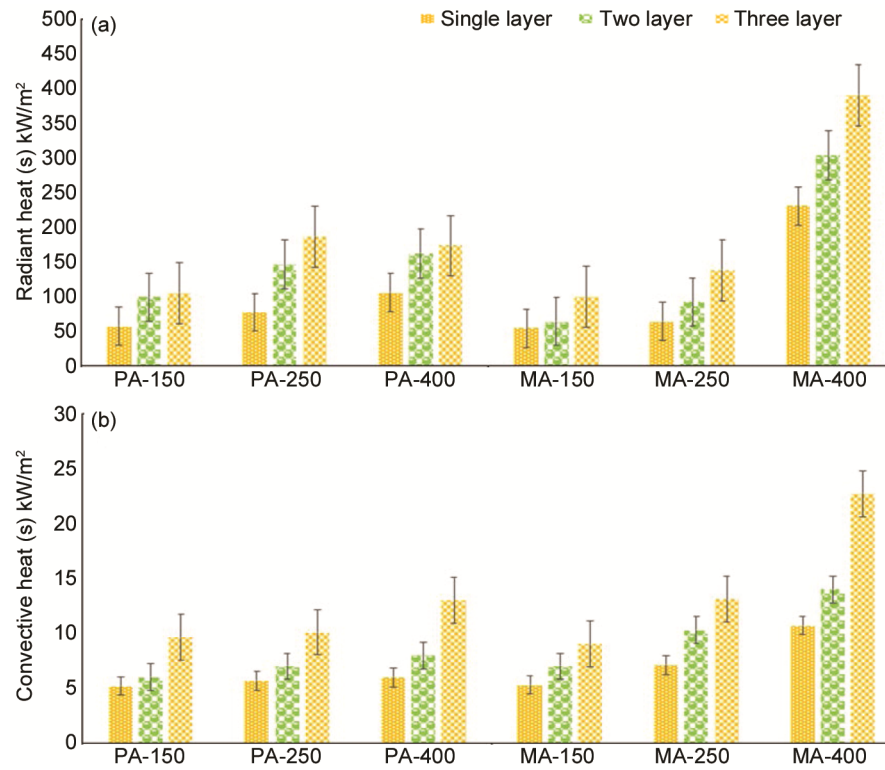


Fig. 6 — (a) Radiant heat and (b) convective heat of different fabric combinations

way ANOVA is employed to compare differences in experimental conditions, particularly radiant heat flux values.

ANOVA analysis (Table 4) demonstrates that layering (37.77 %) and fabric density (29.20 %) are the most influential factors. Fibre type plays a comparatively minor role, although interactions between fibre type and GSM are statistically significant ( $p = 0.003$ ). These findings underline the critical role of structure and density in ensuring radiant heat resistance.

**3.6 Convective Heat Transmission**

In the multilayer garment structure, a heat flux density of 80 kW/m<sup>2</sup> is applied, with a mean heat transfer index HTI<sub>24</sub> ≥ 9s representing the minimal standards for outdoor firefighting work. HTI<sub>24</sub> ≥ 13s denotes the minimal requirement for protective gear during firefighting and rescue operations in burning buildings. As depicted in Fig. 6(b), certain fabric sample combinations, such as para-aramid fabric with a density of 400 and three layers, and meta-aramid fabric with densities of 250 and 400 with three layers, exceed the standard value for structural firefighter clothing (SFFC) in an overheated environment. However, samples selected for preferential firefighter clothing (PFFC) include meta-aramid fabric with

Table 5 — Contribution (%) of parameters to radiant and convective heat transmissions during heat exposure

Parameter	% contribution	
	Radiant heat	Convective heat
Fibre type	4.20	15.06
Fabric density, GSM	50.81	29.20
Layering	15.31	37.77
Fibre type vs GSM	25.63	9.28
Fibre type vs layering	--	--
Layering vs GSM	--	--

‘--’ indicates the non-significance at a 5 % level and negligible % of the contribution.

densities of 150, 250, and 400 with three layers, and meta-aramid fabric with densities of 150 with three layers, 250 with two and three layers, and 400 with one, two, and three layers.

ANOVA results (Table 5) indicate that layering, fabric density, fibre type, and their interactions significantly impact balaclava performance in highly hazardous environments from convective heat, as evidenced by the significant model F-value and P-value. The percentage contributions of these factors to balaclava performance are approximately 37.77 % for layering, 29.20 % for fabric density, 9.28 % for fibre type, and 9.28 % for interaction. This suggests

that layering and fabric density substantially impact balaclava performance, while the interaction effect is relatively minimal.

#### 4 Conclusion

The study demonstrates that the thermo-physiological comfort and fire-resistant performance of firefighter balaclavas are governed primarily by fabric density, layering, and fibre type, with varying degrees of influence depending on the thermal exposure mode. Para-aramid fabrics exhibit superior flame resistance compared with meta-aramid, attributed to their higher thermal stability and limiting oxygen index, while cotton fails under direct flame but contributes positively to comfort-related properties such as breathability and initial thermal insulation. Air permeability is chiefly controlled by fabric density and layering, with increased GSM and multilayer structures reducing breathability but enhancing thermal protection. Thermal resistance is maximised by multilayer configurations, whereas thermal conductivity is predominantly influenced by fabric density. Contact, radiant, and convective heat transfer tests confirm that only selected high-density, multilayer aramid fabrics meet the stringent NFPA and ISO standards required for structural firefighting, highlighting the importance of optimising structural parameters. In summary, para- and meta-aramid fabrics, when engineered with appropriate density and layering, provide effective fire resistance and

compliance with international standards, making them suitable candidates for firefighter balaclava applications. This research lays a robust foundation for enhancing firefighters' protective equipment by furnishing actionable recommendations for optimising balaclava design.

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