Design and Application of Fire-Retardant Sweater Using Polyimide Fabric for Fire Fighters

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Abstract: To protect fire fighters' security in city and forest, the auxiliary equipment was studied. Firstly, the traditional wool sweater and cotton-padded suit were reviewed. Secondly, series new fire-retardant sweaters using polyimide fabric was designed for better warmth retention. Finally, different sweaters with short or long polyimide villus were applied in different areas with relative clothing climate zones. The new sweater's parameters like fiber shedding should be examined in the future to ensure its actual effect during the trail in the city and forest forces.

1 INTRODUCTION

Firefighters' job is to extinguish city fires and forest fires. The allocating numbers for city firefighters was shown in Tab 1. To protect fire fighters, fire protective clothing equipment was required. Current aramid sweater had low warmth retention. And the current cotton-padded suit created a lot of deleterious smoke. So new fire-retardant sweater using polyimide was required with high warmth retention and little smoke.

Theoretically, the outer equipment like fire protective clothing could help people to keep his safety from fire radiation and fire flame. However, the fire fighters' skin might be still burnt in large fire scene in extreme circumstances using polyester underwear or polyester sweater. Therefore, protective auxiliary equipment like fire-retardant underwear or sweater for fire fighters was also necessary.

Table 1: Personal protective equipment's allocating number for city fire fighters.

Name	Fire service station class one	Fire service station class two	Special fire service station
Fire protective clothing for firefighter	2 to 1 fireman	2 to 1 fireman	2 to 1 fireman
Protective gloves for firefighters	4 to 1 fireman	4 to 1 fireman	4 to 1 fireman
Adiabatic protective clothing for firefighter	4 to 1 team	4 to 1 team	4 to 1 team
Chemical protective class two ensemble for firefighters	6 to 1 station	4 to 1 station	1 to 1 station
Fire-retardant sweater	-	-	1 to 1 fireman

2 THE TRADITIONAL PROTECTIVE AUXILIARY EQUIPMENT FOR FIRE FIGHTERS

There were generally two type forces including city fire rescue and forest fire rescue. The main different characters were as shown in Tab 2 below. Compared with city fire, the forest fire were generally happened on the site far away from city. Especially, the small scale fire would be put off by forest ranger in Forestry Bureau, people's militia in country and even local villager. The forest fire fighters would

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only put off the large scale fire. The whole fire extinguishing process would last for a few days or even a few weeks. Therefore, the fire fighters in forest fire rescue force paid more attention on their equipment's warmth retention during their sleep in the wild.

Table 2: The difference between forest fire fighters and city fire fighters

Parameter	**Forest fire fighter**	**City fire fighter**
Fire extinguishing place	Forest or grassland far away from the city	City building or chemical plant near city
Fire extinguishing time	A few days or even a few weeks	A few days
Work environment	Complex field temperature like cold	Complex field temperature like cold
Rest place	Field camps	Dormitory
Rest environment	Might be cold with high humidity	Comfortable

2.1 The Traditional Fire-Retardant Sweater Using Wool as City Fire Fighters Protective Auxiliary Equipment

According to *Firefighter Protective Auxiliary Equipment Fire-Retardant Sweater* XF 1274-2015, the flame-retardant sweater was designed using 99.5% wool fiber and 0.5% polyester conductive fiber. The relative standard didn't make specific request to wool fiber's warmth retention as shown in Tab 3. Then the experiments on fire-retardant sweater were carried out to determine its warmth retention.

Table 3: The requirements of fire-retardant sweater using wool

Parameter	Data	Testing method	Note
Warmth retention	Thermal resistance rating (100±10)%	Gb 11048	Clause 6.2
Flame retardant	LOI ≥ 28	GB 5454	Clause 6.3
Flame retardant	Afterflame time ≤2 s no droplet	GB 5455	Clause 6.3
Bursting strength	Bursting strength ≥300 N	GB 7742	Clause 6.11
Electrostaic property	One sweater's electricity≤0.6μC	GB 19976	Clause 6.11

The thermal resistance can be defined as a parameter to characterize clothing's warmth retention. To fire protective clothing with four layers, the thermal resistance was about 0.0541 $m^2 \cdot K/W$. To traditional wool sweater with one layer as shown in Fig 1, the thermal resistance was only 0.0651 $m^2 \cdot K/W$. Although this wool sweater was fire retardant and had little smoke during its burning process. Its low thermal resistance should be still paid attention. This parameter thermal resistance for wool sweater should be improved by modifying. The new fabric material with lower thermal conductivity should be introduced and the structure of shorter villus of woolen fabric should be modified.

Figure 1: The fire-retardant sweater using wool and cotton-padded suit using modacrylic fabric

2.2 The Traditional Fire-Retardant Cotton-Padded Suit for Forest Fire Fighter as Forest Fire Fighters Protective Auxiliary Equipment

Before 2015, the fire retardant cotton-padded suit were prepared for the forest fireman for cold sleep in the field by introducing modacrylic fabric. This material could be obtained by acrylonitrile and fire retardant ethylene. This fabric's prize was relative low and most of the forest fire fighters were equipped before 2015.

This fabric had good thermal resistance 0.202 m^2·K/W, but its warmth retention would decrease to 0.108 m^2·K/W gradually because of its hygroscopicity in long time serving. Moreover, this modacrylic fabric would generate more black smoke. This deleterious HCN smoke would affect fire fighters' breathing. So the thermal resistance for cotton-padded suit should be improved.

3 THE NEW FIRE-RETARDANT SWEATER USING POLYIMIDE FOR FIRE FIGHTER

To improve new sweater's thermal resistance, the different fire-retardant fabrics were considered to take the place of wool fabric in sweater or modacrylic fabric in cotton-padded suit. The parameters of functional fabrics were as shown in Tab 4.

Table 4: The parameters of functional fabric

	Aramid PMIA	Aramid PPTA	Polysulfonamide PSA	Polyimide PI
Density g/cm^3	1.38	1.45	1.40	1.41
Long time thermal stability °C	230	190	200	280
Short time thermal stability °C	260	260	290	＞300
Resistance to ultraviolet radiation heat	Bad	Bad	Good	Good
Moisture regain	4.5%	4.5%	6.3%	3.5%

The first functional fabric was aramid fiber whose structure had at least 85% of the amide linkages attached directly to two aromatic rings. Then its short time thermal stability could reach 260°C with LOI 28. However, its heat thermal conductivity could even reach 0.045 W/m·K. Therefore, aramid fabric was not the suitable fabric material to new sweater.

The second functional fabric was polysulfonamide. This fabric could be prepared by interfacial polymerization of polyethylenimine and benzene-1,3-disulfonyl chloride. Then its short time thermal stability could reach 290°C with LOI 33. Its heat thermal conductivity could reach 0.033 W/m·K. Therefore, polysulfonamide fabric was the suitable fabric material to new sweater.

The third funciton fabric was polyimide. The π-π interactions between aromatic rings guarantee this fabric's thermal functions. Its short time thermal stability could be higher than 300 °C with LOI 38. Its heat thermal conductivity could reach 0.040 W/m·K. Therefore, polyimide fabric was also the suitable fabric material to new sweater.

Considering the fabric's mechanical property and spinnability, polyimide was chosen to produce new sweater. In addition, there was little balck smoke during the polyimide fabric's burning process. According to polyimide villus' length, there were two types of fire-retardant sweaters.

3.1 Fire-Retardant Sweater with Long Villus Using Polyimide

To polyimide sweater, there were two parts in the clothing including ground yarn and veil yarn. The ground yarn should had better bursting strength to maintain the clothing's elasticity. Then the flame retardant polyester fabric with elastic strength was introduced. The veil yarn should had better warmth retention to guarantee the sweater's thermal property. Then the polyimide fabric and antistatic polyester fabric were introduced.

One type clothing was the sweater with long polyimide villus as shown in Fig 2. The long villus could guarantee its thermal resistance to 0.201 m^2·K/W. To keep the sweater's antistatic property. Not only the antistaic polyester fabrics were introduced in the veil yarn with poylimide, but also the antistatic polyester yarn and elastic polyester filament were double twisted in the ground yarn. Then this new sweater's surface electricity could be lower than 0.6 μC. The longer of the polyimide villus, the easier losing of the fabric during the long time serving. The fiber shedding was obvious.

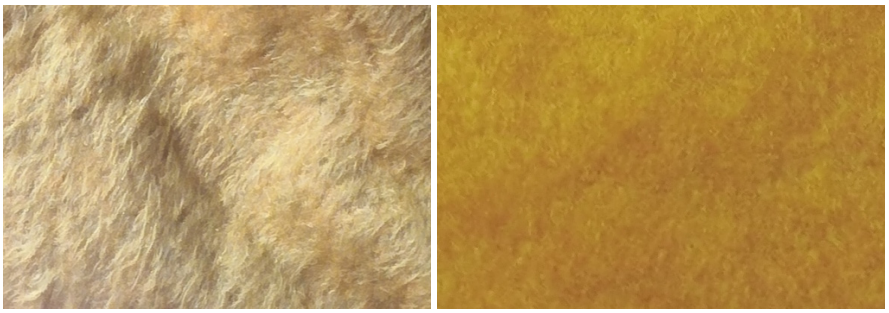

Figure 2: The fire-retardant sweater using long polyimide villus and using short polyimide villus

3.2 Fire-Retardant Sweater with Short Villus Using Polyimide

The other type clothing was the sweater with short polyimide villus as shown in Fig 2. The veil yarn were generally produced by polyimide fabric and fire retardant viscose. The introduction of viscose could be used to improve sweater's skin affinity. Then the whole sweater with short polyimide villus could reach 0.132 m^2·K/W. Compared with the veil yarn using 98% polyimide fabric in the first type, the second type sweater used only antistatic polyester in the veil yarn except ground yarn. Then this new sweater's surface electricity could also be lower than 0.6 μC. Although this sweater with short polyimide villus had lower warmth retention, the short villus could be stable during the long time servicing.

4 APPLICATION OF NEW FIRE-RETARDANT SWEATER USING POLYIMIDE

According to *The Requirements on Insulation of Labour Protective Clothing in Cold Condition* GB13459, different areas with relative clothing climate zones were as shown in Tab 5. Considering the outer protective clothing and inner thickened underwear, the sweaters with different length villus were recommended with different retention. The fire-retardant sweater's trail in Heilongjiang's city firefighters and Sichuan's forest firefighter were shown in Fig 3.

Table 5: The climate zones in China

Climate zone	Area	Synthetic temperature	Warmth retention
V	Between Mohe and Harbin	<-25°C	1.01 m^2·K/W
IV	Between Harbin and Zhangjiakou	Between -15°C and -25°C	0.89 m^2·K/W
III	Between Zhangjiakou and Zhengzhou	Between -5°C and -15°C	0.72 m^2·K/W
II	Between Zhengzhou and Fuzhou	Between 5°C and -5°C	0.59 m^2·K/W
I	Between Fuzhou and Haikou	>5°C	0.45 m^2·K/W

For example, in the city of Altay with synthetic temperature -21°C in IV climate zone, the required warmth retention was 0.89 m^2·K/W in static condition. The forest firefighters or city firefighters' fire protective clothing's warmth retention was 0.05 m^2·K/W. The thick underwear's warmth retention was 0.05 m^2·K/W. Then the new sweater and thick flocculus-padded suit with 0.60 m^2·K/W should be applied together in winter. The new sweater's warmth retention should be higher than 0.19 m^2·K/W. Then the sweater should be with long polyimide villus in the area between Zhangjiakou and Mohe.

Figure 3: The fire-retardant sweater's trail in Heilongjiang's city firefighters and Sichuan's forest firefighter

For example, in the city of Nanjing with synthetic temperature -3.2°C in II climate zone, the required warmth retention was 0.45 m^2·K/W in static condition. The forest firefighters or city firefighters' fire protective clothing's warmth retention was 0.05 m^2·K/W. The thin underwear's warmth retention was 0.02 m^2·K/W. Then the new sweater and flocculus-padded suit with 0.25 m^2·K/W should be applied together in winter. The new sweater's warmth retention should be higher than 0.13 m^2·K/W. Then the sweater with short polyimide villus could be used in the area between Haikou and Zhengzhou.

5 CONCLUSION

To keep forest and city fire fighters' security, the auxiliary equipment were studied on the base of wool sweater and cotton-padded suit. The new fire retardant sweater using polyimide were produced with better warmth retention. New sweater with long polyimide villus could be used in climate zone V and IV with thick flocculus-padded suit. New sweater with short polyimide villus could be used in climate zone II and III with thin flocculus-padded suit. The further study should focus on the actual application of polyimide sweater in moving condition instead of static condition. And the other comfortable parameters including fiber shedding, skin affinity and moisture regain should also be studied.

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