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Recent trends and future scope in the protection and comfort of fire-fighters' personal protective clothing

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Abstract

Fire-fighters' personal protective clothing is the only source of protection for fire-fighters during fire-fighting. The protective clothing should provide adequate protection as well as should be comfortable to wear. The protection and comfort requirements are always the contradicting fact in several protective clothing including fire-fighters'. Appropriate material selection, clothing design and final evaluation of the results play a critical role in predicting the clothing performance and comfort. Several researches have been done on the performance and comfort improvement of fire-fighter's protective clothing. However, detailed review related to these parameters is not being reported in recent years. In this perspective review, we report the recent trends in the performance and comfort properties of the fire-fighters protective clothing. The clothing design and different materials used to achieve a balance between performance and comfort is illustrated. Various test standards related to the performance and comfort is also being discussed. In addition, the future scopes and challenges while designing tomorrows advanced protective clothing are cited. This would provide a guideline in terms of comfort and performance while developing and designing the fire-fighter protective clothing for different climatic conditions.

Keywords: Fire-fighters' protective clothing; Test standards; Heat stress; Performance; Comfort

Introduction

Fire-fighters encounter a range of hazards during structural as well as wild-land fire-fighting. The hazards can cause minor injuries to fatal accidents leading to end of career or even death of fire-fighters. Personal protective equipment (PPE) and personal protective clothing (PPC) are the materials which create a barrier between the hazardous environment and the fire-fighter for protection (Scott 2005). The performance level of PPC is the most important factor, which determines the life/injury saving potential of the clothing. The performance level depends on the nature of fire, type, design and characteristic features of the PPC (Kilinc 2013).

Wearing protective clothing is essential to protect the fire-fighters from thermal exposures and other life threatening risks. In general, the standard protective clothing is a multilayer construction, which is heavy and bulky to provide the desired thermal protection. This in turn reduces the ability of the protective clothing to transfer internal heat to the surrounding atmosphere and creates heat stress to the fire-fighters. Hence, the moisture produced by sweating remains inside the clothing system resulting in a sensation of wet clinginess and thermal discomfort to the wearer. Therefore, optimizing the thermal protection and comfort properties of the PPC have been the major area of research in recent years. The comfort properties of the fire-fighters personal protective clothing (FFPPC) is a complex phenomenon governed by the transport properties and thermal resistance of the fabric combinations. An ideal clothing will provide the necessary protection as well as minimize the metabolic heat stress. However, these are the two conflicting factors to be considered while designing protective clothing for fire-fighters (Scott 2005).

It is important to be aware of the difference between requirements of the clothing needs for different fire-fighting and environmental conditions. The ideal fire-fighters' protective clothing system should confirm to all of the following requirements: (1) radiant and convective

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heat resistance, (2) impact and abrasion resistance, (3) comfort in various weather conditions, (4) water repellency, (5) ease of cleaning, (6) resistance to chemicals, (7) durable with reasonable cost, (8) resistance to spark damage, (9) adjustable ventilation cooling and (10) flame resistance (Prasad et al. 2002; Kilinc 2013).

In active working situation, the performance of a fire-fighter is synonymous with its comfort characteristics. The main concern in the clothing system is to provide complete protection from heat exposure while dissipating sufficient metabolic heat to the environment. Therefore, the main aim is to address these two contradicting requirements. Most of the FFPPC commercially available either fulfill or can be designed to fulfill the performance requirements. However, simultaneously achieving both comfort and protection performance is rather difficult.

Generally, three different aspects such as psychological, physiological and ergonomic can define wear comfort for fire-fighters (Slater 1977). Thermal insulation, breathability, heat transportation of a fabric affects the physiological comfort. This type of comfort is extremely important because of its major effect on fire-fighters work efficiency and performance. Physiological comfort refers to sensation of hot, cold or dampness in clothes and is usually associated with both environmental factors (such as heat, moisture and air velocity) and breathability of the fabric ensembles.

Most of the FFPPC contain moisture barrier layer to improve the heat resistance and more importantly prevent penetration of chemical spillage and reduce steam burn (Song et al. 2008). However, this layer is semi permeable or impermeable to water vapour, which causes considerable discomfort as it is impossible to expel high quantity of sweat from the clothing system. Heat and moisture transfer through clothing involves complex process and is coupled with evaporation, condensation, absorption and desorption of moisture. When these parameters are not balanced, the sweat can accumulate on the skin and inner layer of the clothing system and result in saturation of undergarment microclimate. The high humidity content of undergarment microclimate can lead to the sensation of wetness and increase wearer discomfort.

In this review we will summarise the fire-fighters' protective clothing systems and address the clothing that are in use. Different materials and designs currently in use for the FFPPC are also being covered. This review will also focus on the test methods used for characterising the fire-fighters' protective clothing in terms of heat and comfort. In addition, the future scopes and challenges while designing tomorrow's protective clothing are being cited.

Protection and fire-fighter's clothing

Different types of fire-fighting include structural, wild-land, aircraft fires, vehicle fires and some other type of fires. The amount of time the fire-fighters spend in fire-fighting is only about 5–10% of their duty time where they are exposed to extreme heat and flame (Scott 2005). The major hazards during fire-fighting are from radiant or convective heat, explosions, falling objects, debris, fine air-borne particles, limited oxygen supply, hot liquid, molten substances, noise, toxic chemicals, smoke and hot gases (Melius 2000; Szubert and Sobala 2002; Holmér and Gavhed 2007; Hong et al. 2008). All the hazards encountered by fire-fighters can be classified as thermal, mechanical, chemical, ergonomic and psychological (Guidotti and Clough 1992). The nature and characteristics of the hazards is hard to define as fires vary in types in addition to varying environmental and physical factors.

Various factors such as the burning material, the combustion behaviour of the fire, presence of fuel and toxic chemicals, the fire structure, the measures taken to control the fire, the presence of victims to be rescued and the line of duty held by the fire-fighters affect the level of exposure of the fire-fighters. The major concern for fire-fighter is the thermal exposure, which results in heat stress. Heat can be transferred from the source of fire by conduction, convection or radiation or in combination. It has been shown that exposure to a radiant heat at the level of 4 kW/m^2 can cause second degree burn to bare skin in 30 seconds. In addition, if the heated air is inhaled, it cools down as it passes through the larynx (Genovesi 1980). The dry air can't retain much heat and delivers little heat to the lower repertory tract, hence is not a potential threat. However, as the hot wet air or steam can carry more heat energy, can cause serious burn injuries to the lower respiratory track.

The normal working period for wild-land fire-fighting is 8–16 hours in a day, where they are exposed to an average radiant heat flux of 1–8 kW/m^2. In extreme fire conditions, they can be exposed to radiant heat fluxes in the range of 20–100 kW/m^2. This can be even higher in some instances where synthetic building materials and finishes have been used. While extinguishing fire, flash fire is the other possible hazards that fire-fighters may face. The heat intensity at flash fires is about 80 kW/m^2 and it lasts for a few seconds. Such high heat flux can lead to thermal or life risk injuries. The general injury involves burns of varying degrees due to the prolonged exposure to the thermal hazards. The PPC is essential to protect the fire-fighters from thermal hazards and other life threatening risks.

The major requirement of PPC used for fire-fighting is to provide maximum thermal protection from fire, simultaneously minimising the metabolic heat stress (Guidotti and Clough 1992; Selkirk and McLellan 2004). During fire-fighting, the rate of metabolic heat production rapidly increases. Hence, the only way to maintain thermal balance is to loose heat by sweating at high rates of 1–2 L/hr (Budd et al. 1997). Hence, the heat stress is resulted by the external radiant heat in addition to the body metabolic heat. The heat stress faced by the fire-fighters has been reported by several researchers (Faff and Tutak 1989; Cheung et al. 2000; McLellan and Selkirk 2004; Kales et al. 2007; Cheung et al. 2010).

Various approaches can be adopted for reducing the heat stress, which includes passive recovery (Selkirk et al. 2004; Carter et al. 2007; Barr et al. 2009), the use of extractor fans (Carter 1999), misting fans (Selkirk et al. 2004), immersion of hand and forearm in water (McTiffin and Pethybridge 1994; House 1996) and combined cooling (Barr et al. 2008; Barr et al. 2009). In addition, the use of ice, ice vests (Smolander et al. 2004), cold air and phase change materials (PCM) (House 1996; Smolander et al. 2004; Rossi and Bolli 2005; Carter et al. 2007; Chou et al. 2008; Gao et al. 2012; McCarthy and di Marzo 2012) in the vests worn during fire-fighting activities have been reported The use of cooling vests (Gao et al. 2010) and shorts under FFPPC has also been reported (McLellan and Selkirk 2004; Selkirk et al. 2004).

All these above mechanisms can improve the micro-environment of the human skin and alleviate heat stress. The use of some of the personal cooling devices has been found helpful in several instances. Selecting suitable fabrics for fulfilling these two contradictory requirements is rather difficult. The advancements in the production of new types of thermal resistant fibres can help to achieve improved protection. Furthermore, the use of super absorbent fibres (SAF) and coolmax® fibres has been reported to improve the comfort aspects by reducing the heat stress. The use of multilayer fabrics with each layers performing a different function, can fulfil the requirements of performance and comfort. The density of these multilayer FFPPC can range from 74 to 597 kg/m^3 (Kutlu and Cireli 2005) and the total weight can be higher than 3 kg (Reischl 1982).

Both the radiant heat and metabolic heat can cause health problems to fire-fighters (Rossi 2003). In majority of the fire-fighting conditions, the ambient air temperature is much higher than the human body temperature. In this condition the temperature gradient between the skin and environment becomes negative. Hence, the metabolic heat loss from the human body reduces drastically and even there is a heat gain by the body (Carter et al. 2007). This is being compensated by the sweating ability of the human body. In addition, the human body has a high capacity for evaporative heat loss to the environment, which helps in maintaining the thermal balance (Woodcock 1962).

Although the use of appropriate multilayered textile materials can help to achieve a high level of thermal protection, the transfer properties of these materials are compromised. The multilayered protective clothing can prevent the air and water vapour transport, which results in increased thermal stress and reduces the work efficiency of the fire-fighters (Havenith 1999). Failure to achieve a thermal balance will result in heat stress and saturation of the microclimate close to the skin with high humidity and condensation of liquid from the sweat on the skin (Nunneley 1989). This can lead to high thermal load and discomfort, which in turn restricts the work time of fire-fighters. Hence, the recent designs should not only focus on the protection but also consider to reduce the heat stress (Holmér 1995). The heat stress can be measured from the heart rate and the core body temperature (Bruce-Low et al. 2007). The amount of heat stress depends on the ability of the fabric to transfer the heat and moisture vapour from the wearer's skin to the environment. The parameters affecting these properties are thermal resistance (Rct) and moisture vapour resistance (Ret) (Lotens and Havenith 1991), which are discussed in subsequent section on comfort.

Song et al. (Song et al. 2010) evaluated the thermal protective performance of fabric systems under low level thermal hazards in the range of 6.3–8.3 kW/m^2 by laboratory simulation study following ASTM F 1939 (radiant heat resistance test) and a modified method to capture the contribution of energy stored in the test specimens to skin burn injury. The test was performed on both dry and wet specimens. A water cooled heat flux sensor was used to calibrate the radiant heat source and to measure the energy directly transmitted through the clothing during the exposure and discharged later from the fabric systems. The study established that a typical three layer thermal protective clothing system is required to protect the wearer from skin burn injury even at a low level of radiant thermal exposure. During exposure to heat, the accumulated thermal energy in the fabric system could naturally discharge after the exposure and cause skin burn. This in turn lowers the protection level of the clothing to 0.5 to 3 min from 1 to 5 min calculated from the test results. Several other research have been performed to evaluate the protective performance of FFPPC (Keiser et al. 2008; Song et al. 2010).

The protective performance of the FFPPC is greatly affected by the presence of moisture. The amount of moisture and its distribution; the material used for the clothing system and the clothing design; and the thermal intensity affects the level of thermal protection of the FFPPC (Mell and Lawson 2000; Lawson et al. 2004; Barker et al. 2006). Accumulated moisture on the skin and in the fabric ensembles can alter the level of protection. In a clothing system, the moisture is created from the internal (by perspiration) as well as the external (environmental factors such as water spray from hoses, rain, dew and moisture in the air) sources. The degree of moisture absorption, location and amount of moisture in the body, source of moisture and duration of exposure to thermal radiation affects the moisture transfer through a clothing system to the environment.

The effect of moisture on the transfer properties (such as heat and water vapour) of clothing systems at lower temperature (21–35°C) has been extensively investigated and the mechanism is well known (Farnworth 1986; Gibson 1993; Parsons 1994; Weder et al. 1996; Yoo et al. 2000; Fan and Chen 2002). However, this phenomenon is rather complex when fire-fighting is considered as it involves high temperature. Hence, for effective design of the FFPPC, it is essential to understand the effect and mechanism of moisture transfer through the clothing system at high temperature. Some of the researchers have focused to establish a relationship between the presence of moisture and transfer properties of clothing at high temperature by evaluating properties such as heat transfer index (HTI), thermal protective performance (TPP) and radiative protective performance (RPP) (Lee and Barker 1986; Veghte 1987; Havenith et al. 1990; Rossi and Zimmerli 1996; Torvi and Dale 1998; Lawson et al. 2004).

The effect of moisture (both internal and external) on heat transfer from convective and radiant sources through single-layered (Lee and Barker 1986, Song 2007), two-layered (Lawson et al. 2004), three-layered and four-layered protective clothing systems has been studied. It has been established that moisture can affect both positively and negatively on the thermal protection performance of the clothing systems. The presence of moisture in the clothing system can improve the thermal protection under low radiant heat (Lawson et al. 2004).

Majority of the FFPPC are designed to protect from thermal hazards. Protection from toxic chemicals and mechanical damage can be achieved by special fabrics and chemical treatments. If the fire involves any toxic chemical, the risk and hazards increase the as the nature of chemicals are not known. In some countries such as UK the 'Hazchem' code plates are fitted to the road tankers, which provide information on the nature of fire and level of hazard. In several instances, the smoke from the fire contains toxic gases such as carbon monoxide (CO), carbon dioxide (CO_2), benzene (C_6H_6), hydrogen cyanide (HCN), hydrogen chloride (HCl), sulphuric acid (H_2SO_4), hydrogen fluoride (HF), acrolein (C_3H_4O), methane (CH_4), formaldehyde (HCHO) and polynuclear aromatic hydrocarbons (PNAs) (Gold et al. 1978; Treitman et al. 1980; Brandt-Rauf et al. 1988; Bolstad-Johnson et al. 2000). Special breathing apparatus are needed to overcome the health hazards related to the smoke of these gases which are discussed subsequently in this section.

The composition of smoke varies depending on the nature of the fire, hence the degree of toxicological effects on the respiratory system. The toxic gases can lead to health hazards or even deaths. One of the major factors contributing to the mortality and morbidity of fire-fighters is hypoxia caused by reduced oxygen concentration, which creates confusion and makes difficult to escape (Brandt-Rauf et al. 1988). The other health hazards encountered by fire-fighters can be classified as physical, chemical, thermal, ergonomic or psychological and may include cardiovascular, pulmonary and other disorders (Brandt-Rauf et al. 1988; Guidotti 1992; Guidotti and Clough 1992; Materna et al. 1992). Appropriate outfit and devices are essential to protect the fire-fighters from fire hazards.

A detailed investigation was performed by Jankovic et al. (Jankovic et al. 1991) on the type of toxic gases and their effect on the health of fire-fighters. It was observed that CO is the most common gas present in the smoke leading to knockdown. Other gases as listed above were present in the smoke and exceeded their respective short-term exposure limits (STEL) on some occasions. For acrolein, approximately 50% of the knockdown samples exceeded the STEL. Many contaminants found during knockdown were also present in the smoke at much lower concentrations during overhaul, when masks were usually not worn.

The modern fire-fighters are equipped with self-contained breathing apparatus (SCBA) to reduce the effect of some common toxic gases (Guidotti and Clough 1992). The use of SCBA can help to prevent the direct inhalation of these gases (Johnson 1976; Burgess et al. 1977; Selkirk et al. 2004). Pressurised air, oxygen (O_2) enriched air or pure O_2 is used in the SCBA (Louhevaara et al. 1985). Although the fire-fighters are benefitted with the SCBA, they may be over burdened and further stressed depending on the material used, design and model of the SCBA (Bruce-Low et al. 2007; Kahn et al. 2012). Fire-fighters also use night vision tools while working in dark. The use of fluorescent materials and retroreflective materials improves their visibility during day and night, respectively. In addition, the use of fire alarm systems, smoke detectors and modern communication systems has helped to improve the efficiency of fire-fighting. However, the additional devices have added to the weight of the items to be carried out by them increasing the physical exertion. The two major types of fire-fighting are discussed in the following section.

Structural fire-fighting

It is the most common form of fire-fighting. Fire-fighters must face many fire scenarios within different types of structures and there is risk of being exposed to hazardous materials such as flammable liquid spills and explosions. All these emergency situations require that the structural fire-fighter's protective clothing be suitable, comfortable and water resistant (Lawson 1997). Any protective clothing must keep away moisture from the fire-fighter's skin in order to prevent skin burns and provide comfort. In addition, the clothing must protect against a variety of dangers including radiant heat, flame exposure, and hazardous materials exposure. The fire-fighter's protective clothing for wild-land fire-fighting should fulfil the following requirements (as per ISO TC 94/SC 14/WG 3):

1. Protect fire-fighters from radiant heat,
2. Minimise the risk of burn injuries,
3. Minimise the chance of heat exhaustion,
4. Should be light and loose fitting,
5. Should be well ventilated and allow sweat evaporation (i.e. permeable to water vapour),
6. Should allow evaporation of 1–2 L of sweat/hr,
7. Should dissipate metabolic heat, and
8. Should maintain a thermal equilibrium and comfort in a wide range of fire intensity, climatic conditions and duration of work.

For the purpose of protection and comfort, the fire-fighter's protective clothing used for structural fire-fighting is usually comprised of multiple layers (Lawson 1997). It consists of a flame resistant outer shell and a thermal liner composed of a moisture barrier, a thermal barrier and a lining material (Figure 1) (Lawson 1997). The outer shell utilises aluminised surface to reflect radiant heat and provides thermal resistance; mechanical resistance to cuts, tears and abrasion; and flame resistance (Gagnon 2000). Inherently flame resistant fibres such as para- and meta-aramids, polybenzimidazole (PBI) and some blends are used as outer layer. The PBI fiber developed by Celanese can absorb more moisture than cotton and has a comfort rating equivalent to that of 100% cotton materials. Some fibres can be applied with flame retardant (FR) finishes (products such as Proban® and Pyrovatex®) to improve the performance.

The outer or exterior layer is the first layer of protection provided by the garment. The materials used in this layer are designed to come in contact with flame and heat without degrading or burning. It means they resist ignition of direct flame contact. Most of the commercial materials used for this layer provide flame and heat resistance without compromising heat loss. This layer is usually water repellent and permeable to water vapour. The common materials used in outer layers design are discussed below:

Nomex®: It is made of aramid fibers and manufactured by DuPont. It is light and has high tensile strength and heat resistance (degrading at 480°C). Nomex® IIIA, is a combination of Nomex and Kevlar (5%) with increased tensile and tear strength. Advance Ultra, is a combination of Kevlar, Nomex and Polybezimidazole in a rip stop weave with water repellent finish. It is also light with high tensile and tear strength and abrasion and heat resistance (570°C) which is manufactured by DuPont. High breathability with low water vapour resistance makes this product suitable for outer layer.

Basofil, is an advanced technology melamine fiber designed to be blended with synergistic high-temperature fibre (Kevlar). It has high thermal and UV resistance. Millenia® XT, is one of the new technologies and is made with a spun yarn consisting of Polybenzimidazole and para-aramid staple fibres. It is lightweight with high thermal resistance (700°C). Polybenzimidazole and its matrix are light weight, flexible with excellent mechanical properties, high thermal resistance (700°C) and low UV resistance. Conex®, consists of PBI blended with Kevlar and has high thermal resistance.

Proban® is a cotton treated with FR finishes, possess high breathability and thermal resistance, usually used as one layer for wild-land fire-fighters' clothing as it does not prevent water vapour transfer from the body to the environment. Kermel®, is made of aramid fibres (type of aramid nylon material) manufactured by kermel. It is light and has high heat and flame resistance (1000°C).

The moisture barrier is a light weight web or knitted structure either coated or laminated to the inner side of

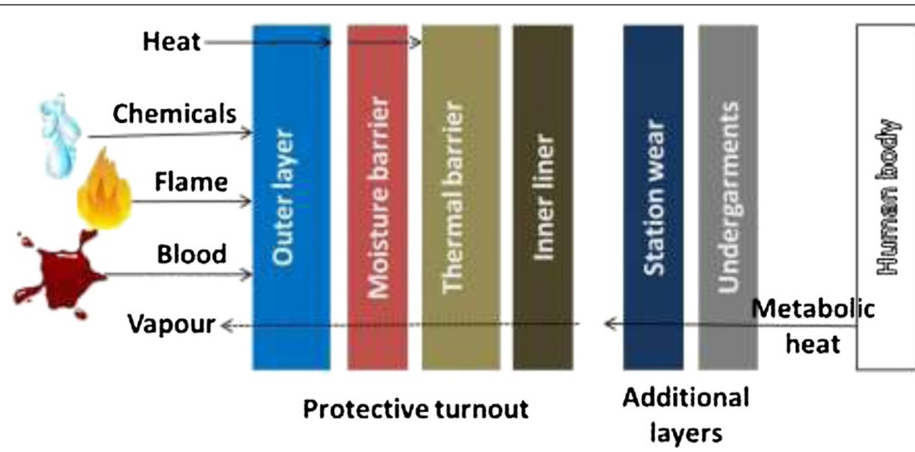

Figure 1 Schematic diagram of FFPPC and function of various layers.

the outer shell fabric. This layer is loosely inserted between the outer layer and the thermal barrier. The moisture barrier provides additional protection against water and many common liquids such as liquid chemicals and blood-borne pathogens. In some countries this layer is mandatory, whereas in some countries it is not preferred due to the thermal discomfort. The moisture barrier can be a hydrophilic or mimicroporous membrane. The commercial names include GoreTex®, Crosstech®, TetraTex®, Porelle®, Proline®, Vapro®, Steadair 2000®, Sympatex®, Action® and NeoGuard®.

The thermal barrier prevents the environmental heat from entering into the body. This layer consists of flame resistant fibres and their blends, which can be of nonwoven, spun-laced, quilted-batting, laminated woven, lining fabric or knitted fabric. The commercial thermal barriers used in the fire-fighter's clothing include GoreTex® (a non-textile material developed by WL Gore Company), Airlock® (a combination of moisture barrier and thermal protection) and Spacers (made of foamed silicone on the GoreTex® moisture barrier to create the insulating air buffer in the material. The inner liner protects the direct contact of fire-fighter with the thermal barrier. The fabric is prepared from fine yarn of Nomex and other fibres (93% Nomex/5% Kevlar/2% antistatic carbon fibre). The use of finer yarns improves the softness and tactile comfort of the fire-fighter and they feel slight slick, which makes donning and doffing easier. This fabric may contain a wick finish, which assists in wicking moisture away from the body.

Wild-land fire-fighting

The wild-land fires take place outside, often in the forest or bush. Wild-land fire-fighters less likely experience the extreme exposure to heat that structural fire-fighters face in a confined space. Wild-land fire-fighters are usually exposed to fire conditions during proximity to the source of fire. However, several other risks are associated with this fire-fighting. The fire-fighters are exposed to a wide range of carcinogenic polycyclic aromatic hydrocarbons (PAH) from the smoke (Rothman et al. 1993). The incomplete combustion of natural material may produce carbon monoxide (CO) (Materna et al. 1993). Exposure to both PAH and CO can be fatal in many instances. The other contaminants include nitrogen oxide, particulate matter, aldehydes and other organic compounds.

Wild-land fire-fighters in several places wear clothing that is usually made up of only the outer layer to protect against radiant and flame impingement, as well as to allow the wearer to maintain cool temperatures, as they must work long hours in dry, hot weather conditions. However, the current designs in several places consist of two to four layers to achieve the performance and comfort requirements (Day and Sturgeon 1987). The clothing system used for wild-land fire-fighting can be exposed to external conditions ranging from completely dry to completely wet. Due to the complexity of these considerations, there may be merit in developing more complex clothing systems that will accommodate all moisture conditions and environments.

During the actual wild-land fire-fighting conditions, the combined exposure to radiant heat and flame lead to the transmission of thermal energy through the fabric, which can cause burn injuries to the skin. Hence, the clothing should have high enough thermal resistance to protect the fire-fighters from the radiant heat. Furthermore, the wild-land fire-fighting is influenced by environmental temperature, air velocity, heat radiation and humidity. External heat sources like radiant heat from fire or the sun can upset the body balance and cause overheating. Hence, it is essential that the clothing provides good insulation from the external heat source in addition to the good conductor of the internal heat. Balance between these two contradictory requirements can be achieved by suitable material selection and design that facilitate evaporation of perspiration and ventilation.

Related standards

There are several standards available on FFPPC for structural and wild-land fire-fighting. Various organisations such as CEN (European Committee for Standardization), NFPA (National Fire Protection Association), ISO (International Standards Organisation), AS/NZS (The Joint Australian/New Zealand Standard) and TC (Technical Committee) issue and manage the standards for the FFPPC. These standards specify the minimal requirements for clothing materials, design and performance specifications. The important requirements set by these standards ensure that all the fabrics, accessories and stitching used in the clothing system should be flame resistant and used materials must not drip or melt at very high temperature. In addition, they should fulfill the performance requirements as mentioned in the standard during fire-fighting. These properties should be permanent and must not be affected by everyday use or laundering. However there is no protective clothing that offers unlimited protection against heat and fire. Table 1 shows the summary of the standards used around the globe for fire-fighters protective clothing. The detailed in-depth discussion of various standards related to fire-fighting is given in references (Hoschke 1981; Scott 2005; Kilinc 2013).

A FFPPC may need to fulfill other requirements such as water repellency, high visibility, antistatic, chemical resistance and biological resistance, which are related to the performance. The high visibility can be an essential requirement in certain places, hence, is not covered in many standards related to fire-fighting. High visibility is

Table 1 Various standards for the specification of fire-fighters protective clothing

Standard	Purpose
ISO/TR 2801:2007 (AS/NZS 2801:2008)	Clothing for protection against heat and flame. General recommendations for selection, care and use of protective clothing.
ISO 11613:1999	Structural fire-fighting (Protective clothing for fire-fighters-Laboratory test methods and performance requirements).
ISO 16073:2011	Wild-land fire-fighting (Personal protective equipment-Requirements and test Methods).
ISO 15384:2003	Protective clothing for fire-fighters-Laboratory test methods and performance requirements for wild-land fire-fighting clothing.
TC 94/SC 13/WG2	Protective clothing against heat and flame.
TC 94/SC 14	Fire-fighters personal equipment.
CEN/TR 14560:2003	Guidelines for selection, use, care and maintenance of protective clothing against heat and flame.
NFPA 1851	Standard on selection, care, and maintenance of protective ensembles for structural fire-fighting and proximity fire-fighting.
NFPA 1855	Standard for selection, care, and maintenance of protective ensembles for technical rescue incidents.
NFPA 1951	Standard on protective ensembles for technical rescue incidents.
NFPA 1971	Standard on protective ensembles for structural fire-fighting and proximity fire-fighting.
NFPA 1976	Standard on protective ensemble for proximity fire-fighting.
NFPA 2112	Standard on flame-resistant garments for protection of industrial personnel against flash fire.
NFPA 2113	Standard on selection, care, use, and maintenance of flame-resistant garments for protection of industrial personnel against short-duration thermal exposures.
AS/NZS 4967:2009	Protective clothing for fire-fighters-Requirements and test methods for protective clothing used for structural fire-fighting.

TC: Technical Committee, SC: Sub-Committee, WG: Working Groups, TR: Standardised document for information and transfer of knowledge, CEN: European Committee for Standardization, NFPA: National Fire Protection Association, ISO: International Standards Organisation, AS/NZS: The Joint Australian/New Zealand Standard.

added to the clothing where the occupational hazards need high visibility.

Comfort and fire-fighter's clothing

The acceptance of fire-fighter's protective clothing depends on the performance as well as the degree of comfort. However, these two requirements are contradicting and for heat and flame protection this becomes more obvious. The clothing should protect from flame and prevent the external heat entering the body. In addition, it should allow the flow of excessive metabolic heat which indicates low thermal resistance and high water vapour permeability. The essential comfort requirements of FFPPC are discussed in the following section.

Thermal comfort

The maintenance of thermal balance is one of the most important aspects of apparels (Slater 1977; Nayak et al. 2009), which is now gaining impetus for various protective clothing such as FFPPC. Body metabolism, clothing transport properties and ambient conditions affect the thermal balance. In addition, suitable combinations of clothing materials and garment structures can facilitate the evaporation of perspiration through FFPPC, hence maintain thermal balance.

It is a well-known fact that the high level of protection is achieved with the compromise of the physiological comfort of fire fighters. This in turn reduces the work efficiency and shortens the working period of fire-fighters. In addition to the mechanisms described above, the following approaches can also help to reduce the level of heat stress or physiological discomfort: (a) Designing special PPC with less thermal impact, (b) Reducing/controlling the exposure level, and (c) Environmental control. The selection of advanced materials (both for performance and comfort) and appropriate clothing design can help in reducing the heat stress. The other approach to this problem is controlling the level of exposure or environmental conditions. In both the approaches, the thermal load is reduced by shortening the time of exposure and/or changing the ambient conditions. The quantitative assessment of these approaches requires a method that takes into account the important factors in a way relevant to the physiological effect. Changing the environmental conditions is rather difficult, which leaves the scope for appropriate design of the FFPPC for a certain degree of exposure. The clothing transport and moisture management properties are the essential parameters affecting the thermo-physiological comfort properties.

Transport properties

A fabric's transport properties are closely associated with its comfort performance and can be reflected by a combination of air permeability, thermal resistance and moisture vapour evaporation, which are also governed by structural factors (chemical and physical) (Slater 1977; Sun et al. 2000, Yoo et al. 2000; Yoo and Barker 2005). Heat, air and moisture transport through FFPPC is a complex process, which is coupled with evaporation, condensation and sorption and desorption of moisture (Holmer 2006). Air permeability allows the air to pass through the fabric, which assist heat loss from the FFPPC. Adequate ventilation can reduce the insulation properties of clothing as well by 5 to 50% (Saville 1999), which may reduce the protective performance of FFPPC. The other problem associated with air permeable fabric is that it may allow the passage of water into the structure, which necessities water proofing. The materials designed to facilitate metabolic heat loss do not necessarily correspond to those required for thermal insulation and water proofing. Hence, these requirements can lead to a comfort/protection paradox.

Thermal resistance (R_{ct}) and water vapour resistance (Ret) of clothing indicate how well it can transport metabolic heat and water vapour to the environment, which affects the thermal comfort during fire-fighting (Prasad et al. 2002). The thermal resistance of a fabric is closely related to the type of fiber, fabric construction and fabric thickness. High thermal resistance, particularly for the inner layer of the protective clothing can result in heat stress. However, for the outer layer, the thermal resistance should be sufficiently high in order to prevent the external heat entering into the body system. On the other hand, water vapour resistance affects comfort properties while sweating and low water vapour resistance is preferred for fabrics used for FFPPC. The water vapour resistance is affected by fiber type; fabric construction and thickness; and number of fabric layers in the final clothing system (Saville 1999).

Moisture management properties

The moisture management properties of a fabric are significantly affected by the type of fiber (Ruckman 1997). A fabric with high liquid absorption and transport properties provides substantial advantage if clothing comfort is considered. Such a fabric is generally considered comfortable and can be selected for the clothing used for the duties involving high activity level such as fire-fighting. The fire-fighters face the risk of scald due to the condensation of evaporated moisture on the skin (Veghte 1987; Kahn et al. 2012). The use of moisture barrier can prevent the sweat to be soaked in the entire garment and keep the wearer dry. The microporous structure of the moisture barrier prevents water moving back towards the skin. It facilitates the water vapour (generated from the sweat) to escape to the environment and thus reduce steam burns and heat stress.

Tactile comfort

Tactile comfort is the feel or sensation by the skin when clothing is worn. The type of fiber, chemical finish, type of fabric and fabric structure affects the tactile comfort (Nayak et al. 2009). The feel of the clothing negatively affects the tactile comfort in two different ways: (a) feel of prickle, tickle or itch (Mattila 2006) and (b) feel of wet clinginess when the fabric is wet (Wang et al. 2013). If the clothing is hard or stiff, the fire-fighters feel prickle or irritation when wear next to the skin. Similarly, the wet clinginess can be a major source of sensorial discomfort for fire-fighters in situations of profuse sweating. The wet clinginess of the fabric is governed by the moisture management properties of the fabric. A fabric may behave differently when it is wet and dry and hence will show different tactile comfort.

Psychological comfort

Fire-fighting in extreme hot conditions can lead to emotional stress of fire-fighters, which has a significant importance on their health and safety as well as that of the crew and the public. Fire-fighters must remain vigilant, make important decisions and remember various geographical or structural features in order to be able to navigate their way out when ambient oxygen levels become low or the conditions become fatal. The cognitive performance of the fire-fighters decreases due to the environmental conditions and levels of dehydration, in addition to the intensity of the work performed during fire-fighting (Bos et al. 2004). The ability to stay focused in task-relevant information reduces during times of increased stress. Profuse sweating during fire-fighting can reduce body mass by about 2% which has an impact on mental concentration and working memory (Rossi 2003).

The impact of heat stress and dehydration affects the mental performance of fire-fighters. The physiological stress, discomfort and psychological aspects (anxiety) can deter their ability during fire-fighting. As the stress level during fire-fighting increases, the task focused thinking reduces (Kivimäki and Lusa 1994). There has been limited research on the effect of decline in mental performance during fire-fighting on the performance. The mental performance declines as the cerebral blood flow is reduced due to the heat stress (Gopinathan et al. 1988), which impacts the cognitive performance. Psychological strain can be reduced by the maintenance of proper hydration levels and active body cooling. As the amount of research on the psychological stress and its impact is limited, the future research should focus on the cognitive function of fire-fighters. This can be performed in climatic chambers in hot conditions while fire-fighters perform physical tasks at the typical duration and intensities that reflect the energy expended during fire-fighting. Computer-based cognitive function tests that have ecological validity can be used to evaluate the stress level and its impact.

Ergonomic issues

Wearing the protective clothing, carrying various fire-fighting aids and dealing with the tasks (fire suppression, search and rescue), impose a high physical burden and demand substantial energy expenditure. The fire-fighters need muscular strength, aerobic fitness, endurance in the upper and lower body, flexibility and a favorable body composition to keep them safe and ensure public safety (Barr et al. 2010). The use of FFPPC is always being an issue when ease of body movement is considered (Coca et al. 2010). The mobility and comfort of the firefighters should not be drastically reduced while designing their protective clothing. Various factors such as the number and thickness of each fabric layer, clothing system design and the relative size between the body and the clothing affect the body movement. As the number of layers or the physical bulk or the overall weight of the clothing system increases, the mobility within the clothing is reduced.

In addition to the clothing (turnout coats and pants), fire fighters use boots, gloves, helmet and carry self-contained breathing apparatus (SCBA), which help them from extreme heat, steam, toxic fumes as well as cold (Lee et al. 2014). However, the fire fighters need additional physical effort to carry these items during the stressful activity of firefighting (Park et al. 2010). Ergonomic design issues such as limited mobility of the head and arms while wearing helmet, and SCBA, restricted access to coat pockets, back pain and soreness while wearing SCBA was reported by fire fighters (Park, Park et al. 2014).

Although the boots provide protection, they may fail to facilitate a normal gait and balance of fire fighters. Designing factors such as the heel height; heel-collar height; sole hardness; heel and midsole geometry; and slip resistance of the outer sole influence fire fighters performance (Menant et al. 2008). Wearing boots (about 4.5 kg) can trigger rapid fatigue which may result approximately nine times greater metabolic rate per unit mass, compared to SCBA. Boot manufacturers have taken initiative to modify the current styles of boots in an attempt to combine the positive characteristics of safety and normal movement. Several research have been done to improve the balance of fire fighters (Punakallio et al. 2003; Punakallio 2005; Perry et al. 2007) and postural control (Punakallio 2005; Garner et al. 2013).

The gloves provide protection from heat, steam, abrasion, cuts, punctures, chemicals and cold. The gloves must provide good manual dexterity, feel and grip without becoming slippery when wet (Park, Park et al. 2014). In a recent survey it was identified that the sizing and fit issues such as the excessive length and bulkiness of glove fingers as a major concern of the gloves resulting in limited mobility and dexterity, negatively effecting firefighters' work efficiency and safety (Park, Park et al. 2014). Carrying SCBA (about 9–13 kg on average) on their back can impair body balance and cause musculoskeletal injuries during firefighting. The body balance of fire fighter's change during motion due to the change of centre of mass, which is a major contributor to fall injuries (Helneman et al. 1989). Park et al. (Park et al. 2010) reported that an increase in weight of SCBA elevates the risk of fall and slip injuries.

Performance evaluation

Evaluating the thermal performance of clothing can be categorised into two groups: (a) small scale and (b) large scale tests. Small scale tests are completed using partial samples of garments. Test methods for fire-fighter clothing with the types of testing are outlined in detail in many standards as listed in Table 2. Small scale testing is an inexpensive way to assess the fabric's level of protection, however, the test has many disadvantages. Materials are located in an apparatus and oriented in a manner that is not representative of normal application of the laboratory instrument. The level of protection of an entire piece of clothing constructed from the fabrics tested cannot be extrapolated from the testing. This is because in each small scale test, materials are tested statistically, which are not accurate representations of garments in real fire-fighting scenarios.

Large scale tests involve dressing a life size manikin with fire-fighter clothing and exposing the manikin to a fire environment. An entire ensemble can be tested rather than just a small piece of material. Since the focus is being placed on full ensemble testing, a series of existing large scale tests are reviewed. The existing large scale tests followed for FFPPC is described in ASTM F-1930, one of the test methods for evaluation of flame resistant clothing for protection against flash fire. The other test method described in ASTM F-1930, describes a simulated flashover environment around a manikin during the test. Some other tests include DuPont Thermo-Man test, Pyroman test, Ralph test and NFPA 1912 test (Sipe 2004; Gašperin et al. 2008).

Various tests can be performed in the fabric stage to predict the performance of FFPPC. In addition to the fabric tests, the thermal manikin tests can also be performed under laboratory conditions to evaluate their performance. However, the conditions that might be encountered during actual fire-fighting may be entirely different from the manikin tests. The manikin tests are also time-consuming and relatively expensive compared to fabric tests. The manikin test may provide additional information on the design and performance of the FFPPC that cannot be obtained from the fabric test.

For structural and wild-land fire-fighters, the protection is measured in terms of Thermal Protective Performance (TPP) rating and Radiant Protective Performance (RPP) rating, respectively. There are several issues with the existing test methods. Firstly, the sensors used have different properties than the actual human skin. The testing also ignores the effect of water on or absorbed in the suit and the compression caused by a fire-fighter's movement, both of which can potentially increase the heat transfer. Secondly, the test does not take into account the effect of clothing layer cooling while still on the skin. Various standard test methods

Table 2 Standard test methods used to evaluate the protective performance of FFPPC

Test standard	Description
ISO 6942:2002	Protective clothing: Protection against heat and fire - Method of test: Evaluation of materials and material assemblies when exposed to a source of radiant heat.
ISO 9151:1995	Protective clothing against heat and flame - Determination of heat transmission on exposure to flame.
ISO 11612:2008	Protective clothing - Clothing to protect against heat and flame.
ISO 14116:2008	Protective clothing - Protection against heat and flame: Limited flame spread materials, material assemblies and clothing.
ISO 12127–1:2007	Clothing for protection against heat and flame - Determination of contact heat transmission through protective clothing or constituent materials-Part 1: Test method using contact heat produced by heating cylinder.
ISO 12127–2:2007	Clothing for protection against heat and flame - Determination of contact heat transmission through protective clothing or constituent materials. Test method using contact heat produced by dropping small cylinders.
ISO 13506:2008	Protective clothing against heat and flame - Test method for complete garments: Prediction of burn injury using an instrumented manikin.
ISO 15025:2000	Protective clothing - Protection against heat and flame: Method of test for limited flame spread.
ISO 17492:2003	Clothing for protection against heat and flame - Determination of heat transmission on exposure to both flame and radiant heat.
ISO 17493:2000	Clothing and equipment for protection against heat - Test method for convective heat resistance using a hot air circulating oven.
ISO 4920/EN 24920	Determination of resistance to surface wetting (spray test) of fabrics (outer layer).
BS EN 367:1992	Protective clothing - Protection against heat and fire: Method for determining heat transmission on exposure to flame.
BS EN 702:1995	Protective clothing - Protection against heat and flame: Test method: Determination of the contact heat transmission through protective clothing or its materials.
ASTM F 1930	Standard test method for evaluation of flame resistant clothing for protection against fire simulations using an instrumented manikin.
ASTM F 1939	Standard test method for radiant heat resistance of flame resistant clothing materials with continuous heating.
ASTM F 2731	Standard test method for measuring the transmitted and stored energy of fire-fighter protective clothing systems.
ASTM F 2733	Standard specification for flame resistant rainwear for protection against flame hazards; section 8, thermal performance testing procedures.
ASTM D 7140/D 7140 M - 13	Standard test method to measure heat transfer through textile thermal barrier materials.
ASTM F1930 - 13	Standard test method for evaluation of flame resistant clothing for protection against fire simulations using an instrumented manikin.
ASTM F1449 - 08	Standard guide for industrial laundering of flame, thermal, and arc resistant clothing.
ASTM F1939 - 08	Standard test method for radiant heat resistance of flame resistant clothing materials with continuous heating.
ASTM F2700 - 08 (2013)	Standard test method for unsteady-state heat transfer evaluation of flame resistant materials for clothing with continuous heating.
ASTM F2701 - 08	Standard test method for evaluating heat transfer through materials for protective clothing upon contact with a hot liquid splash.
ASTM F2702 - 08	Standard test method for radiant heat performance of flame resistant clothing materials with burn injury prediction.
ASTM F2703 - 08	Standard test method for unsteady-state heat transfer evaluation of flame resistant materials for clothing with burn injury prediction.
ASTM F2757 - 09	Standard guide for home laundering care and maintenance of flame, thermal and arc resistant clothing.
ASTM F 2894 - 2014	Standard test method for evaluation of materials, protective clothing and equipment for heat resistance using a hot air circulating oven.
ASTM WK27614	Determination of flame shrinkage of flame resistant materials.
ASTM WK27615	New test method for the evaluation of materials, protective clothing and equipment for heat resistance using a hot air circulating oven.
ASTM WK29697	New test method for convective-thermal protective performance (c-tpp)
ASTM WK33641	New guide for selection and use of flame-resistant garments for protection against combustible dust deflagrations.

devised to evaluate the performance of FFPPC is describe in Table 2.

Comfort and ergonomics evaluation

The thermal insulation of fabric is measured by thermal resistance which is reciprocal of thermal conductivity. The thermal conductivity can be measured by using a tog-meter (using single- or two-plate method) or using the sweating guarded hotplate (SGHP) method. The water vapour resistance can be measured by using the dish method or using the SGHP method. The moisture management properties can be measured by evaluating various fabric parameters such as absorbency, horizontal- and vertical wicking, moisture management (MMT) properties and water repellency (spray rating, WIRA shower test or water repellency tester). Furthermore, the comfort related to wet clinginess can be evaluated by measuring the absorbency and rate of drying of the fabric assemblies.

The skin sensorial comfort is measured by measuring the surface friction and surface roughness of the fabric using KESF module 4, out of the four modules to evaluate various fabric properties (Matsudaira et al. 1985). The detailed test standards used for the evaluation of comfort properties of fabrics and clothing are given in Table 3.

The experiments performed with human subjects wearing the FFPPC are the most appropriate method for comfort evaluation. However, this method is not consistent when repeated as the output depends on the subjects and conditions used. Sufficiently high test subjects with similar gender, fitness and physiology should be included to reduce the variability. Hence, human forms (thermal manikin as shown in Figure 2) are used to avoid the variability arising from subjects and conditions as conditions can be well controlled with the same manikin (Li et al. 2007). Several researches have been done to evaluate and enhance the comfort properties of the fire fighters uniforms by changing the material combination, design features and using the advanced fibers and finishes (Ramirez et al. 1994; Malley et al. 1999; Carter et al. 2007; Coca et al. 2008; Zhang et al. 2009).

Movement analysis method can be used to evaluate the restriction to movement caused by wearing FFPPC. A range-of-motions (ROM) for various body joints is measured using goniometers or other similar instrumentation for movement analysis (Huck 1991). The strain exerted on a garment due to the wearer movement can be evaluated using seamstress analysis or garment slash analysis (McBriarty and Henry III 1992). Additional insight into the problems associated with movement while wearing FFPPC can be obtained by the visual analysis by trained observers (Watkins 1977). The subjective preferences of a wearer can be ascertained from this (Huck 1991). The movement analysis results provide valuable information to investigate a wide range of movements or specifically movements related to the tasks being performed by the wearer (McBriarty and Henry III 1992; Yang et al. 2014).

Influence of environmental factors

Several environmental factors such as wind speed, humidity, temperature and radiant heat (from sun) affect the performance of FFPPC. High wind speeds promote the ignition and rapid spread of wildfires by rapidly drying the fuels and fanning the flames of fires once they are started (Westerling et al. 2004). The behaviour of fire increases in a nonlinear manner with decrease of fuel moisture and increase in the wind speed. In regions that have higher likelihood of experiencing strong winds during drought periods, the prescribed burning will be less effective as such combination is conducive to extreme fire events in intensity and extension.

The humidity, temperature and radiant heat (full sun and fire depends on the distance from the hot surface) are important factors that should be considered for designing the FFPPC system. One of the simple way of considering those factors in designing the protective clothing by testing garments under the estimated wet bulb globe temperature (WBGT) for the specific condition. Furthermore, these environmental factors affect the thermo-physiological comfort properties by influencing the heat exchange between the body and environment as discussed below.

Table 3 Test standards to evaluate the comfort properties of FFPPC

Properties	Test standard	Description
Air permeability	ASTM D 737-96	Standard test method for air permeability of textile fabrics.
	ISO 9237-1995	Textiles-determination of the permeability of fabrics to air.
Thermal insulation and WVP	ASTM F 1868	Standard test method for thermal and evaporative resistance of clothing materials using a sweating hot plate.
	ISO 11092	Textiles-physiological effects-measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test).
	ASTM F 1291	Standard test method for measuring the thermal insulation of clothing using a heated manikin.
	ASTM F 2370	Standard test method for measuring the evaporative resistance of clothing using a sweating manikin.
	ASTM F 2371	Standard test method for measuring the heat removal rate of personal cooling systems using a sweating heated manikin.
	ASTM E 96	Standard test methods for water vapour transmission of materials.
Moisture management property	AATCC 195	Liquid moisture management properties of textile fabrics.
Horizontal wicking	AATCC 198-2011	Horizontal wicking of textiles.
Vertical wicking	AATCC 197-2011	Vertical wicking of textiles.
Drying time	AATCC 199-2011	Drying time of textiles: moisture analyser method.
Absorbency	AATCC 79	Absorbency of textiles.
Physiological responses	ASTM F 2668	Standard practice for determining the physiological responses of the wearer to protective clothing ensembles.

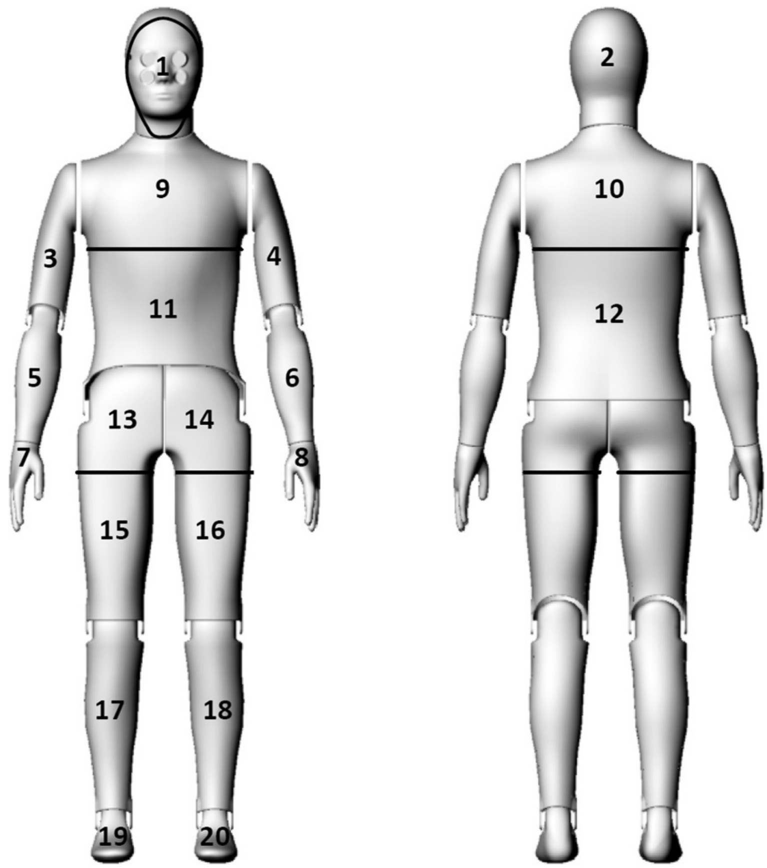

Figure 2 Thermal manikin used for comfort evaluation of FFPPC: left - front view and right - back view.

- Air temperature: It is one of those factors that should be considered for designing and selecting the protective clothing for fire-fighters. In hot environment, above 36°C (e.g. bush fire in summer), the body will gain heat from the environment. Subsequent heat and moisture transfer from body to the surrounding is only possible through evaporation of sweat (Barker 2002, Suprun 2003).
- Absolute humidity: When the absolute humidity is high, the evaporation of sweat is reduced, thereby reducing the body's ability to lose heat (Suprun 2003).
- Radiant heat: It is generated by hot objects such as the sun or fire. The temperature difference between the body and the surrounding determine the direction of the heat flow and is not affected by the air temperature and humidity (Barker 2002).
- Wind or air movement: It has an effect on heat exchange at the exposed skin or outer fabric layer by influencing on both convection and evaporation. Wind usually will move air from the surface and reduce the air temperature. It exacerbates heat losses from convection, radiation and evaporation.
- Other factors: There are few other factors such as physical fitness and clothing, that affects the heat exchange between the body and surroundings (Barker 2002, Suprun 2003).

To determine the overall effect of these factors, a combined measurement approach must be made. Recently, dry bulb temperature (*Ta*) for hot and dry conditions and WBGT index for hot and humid condition is considered to be used, as they address all environmental factors in one index (Patnaik et al. 2006). The difference between the wet and dry bulb temperatures indicates the environments capacity for cooling by evaporation.

Design, sizing and fit

The FFPPC should be designed by taking into consideration the factors such as fire-fighting conditions, ergonomics of movement, heat stress, anthropometry and thermo-physiological behaviour in addition to the protection (Huck et al. 1997, Barker, Boorady et al. 2013). The variables for final design include the number and combination of layers, material types for each layer and total weight of the clothing. As individual fire-fighters body dimensions are different, designing customised clothing is essential to achieve the desired result. The customised clothing can assure proper fit and hence, maximum protection and comfort (Hsiao et al. 2014). Furthermore, correct sizing, appropriate fit and ergonomically designed clothing are essential, as lack of these factors can lead to burn injuries or restrict the movement (Hsiao et al. 2014). For example a FFPPC with too long crotch length may prevent a fire fighter to move freely or may tear making the fire fighter vulnerable to radiant heat. A fire fighter may not be psychologically comfortable to wear a uniform with improper fit.

Easy donning and doffing, collar design and the closure systems, pockets, designing of elbow, underarm, knee area and the crotch are some of the important design aspects to be taken care. The underarm and elbow area can be fitted with bellows and gussets to enhance the mobility. The design should not hinder the use of other assets such as helmet, gloves, fire hood, foot wear and breathing apparatus.

Appropriate sizing is important to achieve the desired level of protection. Correct length of sleeves and pant legs, is essential to provide protection to the wrists and ankles. The FFPPC should be tested for correct fit for the fire fighter before going to the real firefighting (Park and Hahn 2014). During the design and sizing, certain type of fit test should be performed to avoid the fit-problem, which is generally detected only after the final ensembles are manufactured. Anthropometric fit tests should be made mandatory while manufacturing or procuring the protective gear for fire fighters.

In addition, the clothing for female fire-fighters should be designed by taking the female body features into consideration (Boorady, Barker et al. 2013). They should not interfere with the use of boots and gloves. Similarly, pregnant women should be considered during the design process. Consistent sizing practices can develop correct fit and the interface with other safety equipment. As the anthropometric data varies depending on the geographical locations and from person to person, designing customised clothing for individual is essential.

The FFPPC with correct closures and appropriate fullness provides better thermal protection than close fitting FFPPC in flash fire experiments done using manikins (Mah and Song 2010). The thermal protection of loose fitting clothing was attributed to its higher air gaps. The design, style, size and fit affects the air layers between the wearer's body and the clothing, which in turn affects the protective performance. If the clothing is too tight, excessive load is exerted to muscles and body parts, which in turn can lead to fatigue. When tight, heavy and stiff clothing is worn, the metabolic activity of the body increases leading to unwanted heat production. Prolonged wearing of the tight clothing can develop lacerations such as ulcers and pressure sores. In actual fire-fighting conditions, the exposure to flame and radiant heat can cause skin burn injuries.

Careful selection of materials and appropriate design can facilitate the heat and mass transfer from the body. The type of the fibers in various layers, the weight and thickness of fabrics and the final design of the FFPPC are the crucial factors determining the performance and comfort. In addition, the appropriate fit by using the customized measurements for individual fire-fighters can help in this matter.

The technical developments in 3D scanning have helped to design FFPPC with correct sizing and fit. In addition, this has helped to access the air gap distribution in the clothing objectively. The tracer gas method can also be used to determine the ventilation level within the clothing (Havenith et al. 2010). Several studies have investigated the influence of garment fit and air gaps on total insulation of clothing. The mathematical models used to determine the air gap and distribution within clothing is in continuous development and future models will exactly detect these parameters.

Use of smart textiles

Every year many firefighters die around the globe during firefighting. Therefore, the design of smart or intelligent protective clothing system is vital to be able to record physiological data, health and safety such as heart rate or location of the fire fighters without changing its characteristics of flexibility and comfort (Salim et al. 2014). A number of studies investigated the application of wearable sensors under protective clothing; however the enhancement is required to monitor all the vital parameters for firefighters (McLellan and Daanen 2012). For example in fire situation, the sensor will alert the workers regarding the heat exhaustion, hence improve the safety of the fire fighters. As soon as the heart rate and skin temperature increase above the safety threshold, the warning signal will alert the worker, either by vibration, visual or audible signals. Wearable Advanced Sensor Platform is another wearable tracking device, which can track firefighters' location and physical activity (Globe 2014; Salim et al. 2014).

The next generation of protective clothing will be smart protective clothing which interact with the human and environment (McLellan and Daanen 2012). This new generation of protective clothing can sense and react to environmental conditions and be active in many fields. The smart suits can be divided into three subgroups: Passive (only able to sense), Active (reactive sensing to stimuli) and Very smart (able to sense, react and adapt) (Stoppa and Chiolerio 2014). The main parts of the smart textile are sensors, actuators and controlling unit. Sensor provides a nervous system to detect signals and transforms one type of signal into another type (Berglin 2013). There are different type of sensors, such as thermal sensor which detect the thermal changes, pressure sensors, chemical sensors and biosensors. Actuator responds to a detected signal and cause things to change colour, release substance, change shapes or etc. (Cochrane et al. 2011; Berglin 2013). Light emitting diodes convert electrical potential to light and are often used as actuator in smart textiles. Electronics components are required for processing the collected data. This processing unit consists of hardware and software, processing data as well as communication. To supply the power all the electronic components require batteries, which are mostly lithium batteries (Stoppa and Chiolerio 2014).

These units are usually used to monitor physiological parameters, such as heart rate, temperature and blood pressure, to protect the workers from dangerous situations and injuries. One of the projects in this area is CONTEXT (http://www.hitech-projects.com/euprojects/context/). This project was to create a system where different types of sensors are incorporated into textiles to be used in continuous monitoring of individuals. These sensors integrated into textiles to realize a prototype of wearable vest to determine the stress. PROETEX (http://www.proetex.org/) is another project to rescue firefighters by using wireless monitoring of heart rate and temperature measurements. PROFITEX is the project to increase work safety and efficiency of firefighting interventions through advanced protective clothing equipment. In Safe@Sea (http://www.ohmatex.dk/index.php/portfolio/safesea/) project developing a new generation of advances personal protective clothing have been investigated based on the sea. Viking industries (http://cfbt-us.com/wordpress/?m=200908) produced smart protective jackets which sense the temperature and assist firefighters in recognizing dangerous elevated temperatures and in some cases telemetry to transmit this information to others, outside the hazardous environment, based on visual or tactile indicators.

Selection criteria and end of life of FFPPC

In addition to the protection performance and comfort, other essential factors need to be considered while selecting a FFPPC include durability, ease of care, cost, difficulty in production and user preference. The durability can affect the protection and is evaluated by measuring the tensile, tearing and seam strength; abrasion and puncture resistance of the fabric. The selection of FFPPC should also consider the method the garments will be laundered and the potential impact of laundering on the performance. Various standards such as ASTM F 2757–09, ASTM F 1449–08 and NFPA 2113 specify the conditions and methods for the use, care and maintenance of flame resistant clothing.

Cost plays a vital role where the procurement is based on the lowest bid. The tests results for the lowest bid should be carefully analysed before finalising any FFPPC. The major cost is related to the material used in the design of the FFPPC. The approach of blending the costly FR fibers with other cheaper fibers such as comfort fibers can be adopted to reduce the cost and improve the comfort. The process of certifying the compliance to the test standards is also expensive. The clothing systems produced and adopted without any certification can compromise the performance. The items sold with fake or false certification may be cheaper; hence, the items purchased with the lowest bid may not be the ideal ones in several instances.

The production methods involved in FFPPC should be simple and economical. The personal choices can vary while selecting the colour, style and type of garment. In addition, the culture, group identity and gender also affect the selection. For example the FFPPC used in Europe, Asia, Australia and USA differ in their colour and design. In some countries, the colours used for women fire-fighters are not well accepted by the men.

The end of life (EOL) of a FFPPC is difficult to estimate. Although it is easy to locate any mechanical damage such as a rip, tear or abrasion, it is rather difficult to identify the impact of repeated laundering, exposure to ultraviolet (UV) or other radiation and high heat flux. A garment worn frequently at high heat flux may become unsuitable in a shorter period of time. The number of washes, the washing conditions and the amount of UV absorbed by the garment also affect the EOL of the FFPPC. Hence, the EOL can't be defined on the basis of the number of years the garment is in use.

Generally, the EOL is affected by the composition and construction of the clothing; frequency of use; frequency and conditions of washing, nature of work performed, number and types of repairs, fire-fighting conditions and environmental factors (Torvi and Hadjisophocleus 1999). The performance of FFPPC in use has been evaluated by several researchers (Krasny et al. 1982; Rossi et al. 2008; Rezazadeh and Torvi 2011). Parameters such as TTP, flame resistance, seam and tensile strength, tear and abrasion resistance, UV degradation, retroreflectivity, water resistance and zipper operation resistance can be evaluated for this purpose (Torvi and Hadjisophocleus 1999; Thorpe and Torvi 2004; Davis et al. 2010). In several cases it was found that the clothing passed almost all the criterion except the TTP or flame resistance. In addition, a decrease in the seam and tensile strength; and tear and abrasion resistance was observed in many studies (Davis et al. 2010).

Long term UV exposure can damage the fabric due to changes to the molecular structure of the fibres. The fabric becomes weaker gradually and hence, the level of protection decreases. The exposure to high heat flux can also lead to physical or chemical change. In both the cases (UV or heat flux) the overall protection level is decreased. Similarly, laundering conditions, chemicals and agitations also impair the useful properties of the FFPPC. The PPC exposed to biological or chemical contaminants need to be laundered at higher temperature than normal and can degrade the fabric sooner. The nature of the chemical spills, toxic gases and fumes also affects the performance. Considering all these factors, suitable test methods should be devised to detect the EOL of a FFPPC.

Recently, the research has been focused on developing the sensor to alert the wearer's if the clothing reaches to the EOL, due to the exposure to UV, laundering and temperature. UVProText is the only available UV sensor that can be installed on the FFPPC and records absorbed UV by the clothing, number of washing the clothing went through and the exposed temperature. If any of these parameters reaches to the critical values, the sensor alerts the wearer to send the garment for testing.

Future scope

There is always a demand for the fire-fighters clothing with improved safety, comfort and better health. The nature and type of fire is changing especially in structural fire-fighting due to the use of new materials, paints and interior designs. Hence, the protective gear used by fire-fighters need to be modified to protect from these new threats. There is potential threat from chemical, biological and nuclear (CBN) weapons around the globe. The fire-fighters activity is now also being diversified, which may involve operations from CBN threats (Scott 2005). Hence, the newer designs of FFPPC should focus on achieving the protection from CBN threats. Multi-functional and multi-hazard clothing can be developed to provide additional functions. The advancement of technology and creation of new designs can help to meet these requirements.

Various test standards are currently in use for the evaluation of FFPPC. However, the conditions prevailing in real fire-fighting may be different. Hence, the tests standards should be modified to better suit the real conditions. The introduction of new research and development products can alter the nature of the flame. The existing standards should be revised or new standards should be developed to address this issue. In the future the importance of standardisation will increase to achieve the satisfactory specification for protection. Proper coordination between the technology, research and standardisation is needed for future research. Improved protection performance can be achieved with the technological developments.

Test standards as well as test apparatus need to be improved or developed in regular basis. The conditions to which fire-fighters are exposed need to be better quantified and compared to those used in standard tests. The performance tests used to evaluate the fabrics during and after exposure to a high heat flux should continue to be developed or improved. Test standards to evaluate the performance of fabrics primarily with lower radiant heat flux exposure, over a longer duration, should also continue to be developed or improved to provide information about the performance of fabrics under conditions commonly faced by fire-fighters. Various sensors and data analysis techniques should also continue to be improved. Although improved test standards are developed, it remains important that the end-user should keep in mind the limitations of any test method. These include the fact that the conditions under which fabrics or garments are tested will never completely simulate all the conditions that a fire-fighter may face in real working time.

New test apparatus also need to be developed to evaluate the TPP of FFPPC under various working conditions to predict the anticipated hazard. Non-destructive test methods should also be developed for the in-service clothing to rate their performance. For effective evaluation of comfort properties, new test methods should be developed.

The use of electronic textiles can monitor the physiological conditions of the wearer and the environmental conditions. Different sections of application can include: physiological monitoring, locating fire-fighters, predicting the stress, communication and environmental monitoring. A combination of human body sensing, environmental sensing (gases, moisture and temperature) and motion sensing is needed for monitoring fire-fighters at risk. The sensing systems should be designed to monitor record and transmit the information to a central room monitoring the fire-fighters physical conditions for safety reasons. The development in communication systems can help to receive data on the temperature and other hazards they are entering, including the air pressure, heat stress level, ambient temperature and other potential hazards. This will help in the improved fire-fighting conditions and reduce the risk of injuries. Various challenges in designing sensors, connectors, power storage devices, data transfer and storage devices need to be overcome in the successful design of the FFPPC. Table 4 describes the application of various electronic textiles in the future FFPPC to improve the functionality.

The requirements of protection and comfort are almost contradictory as flame resistant fibers are often not comfortable due to the lack of flexibility. Hence, the research and development should emphasize on: (a) to improve the flame retardancy of comfortable fibers mainly by chemical treatment, (b) to improve the comfort properties of inherently flame retardant fibers and (c) to fabricate products with the combination of flame retardant (FR) fibers and comfortable fibers. Products such as FR cotton, FR wool or FR viscose follow the first approach

Table 4 Application of electronic textiles in fire-fighting

Types of application	Effect	Mechanisms
Monitoring health	Physiological process of human body	Electrocardiography (ECG), electromyography (EMG) and electroencephalography (EEG), sweat and temperature measurement
Detecting the location of fire-fighters	Location identification	Wireless devices
Communication	Exchange of information	Wireless and wired devices
High environmental temperature	Heat stress	Active (e-textiles) or passive (PCM) thermal management

and several products are commercially available. However, the second approach is in the recent research topic in several research organisations.

The Effective transfer of moisture vapour and heat stress will be always the challenge while designing the FFPPC. The clothing layer next to skin should have good moisture transport properties such as polyester or polypropylene. However, these fibers melt at much lower temperature. The continual development of new materials, designs and test methods can help to overcome this problem. In addition, the feedback from fire-fighters is also essential while designing the improved FFPPC.

The increase in the breathability and reduction of overall weight of the FFPPC without compromising the protection can help to overcome heat stress. Regular breaks from work (away from heat source) and adequate hydration can also help in reducing the heat stress.

The garment shape can change due to fabric deformations such as bending, stretching, shearing and compression during fire-fighting, which in turn can alter the air gap distribution and hence the thermal protection level. The future research should focus on the effect of mechanical deformation on the thermal protection.

The inherent FR fibers are hydrophobic in nature. The hydrophilic behaviour can be increased by surface functionalization. γ-ray-, UV- or ozone irradiation can be used to improve the surface wettability of the aramid fibers. Recently, plasma treatment is becoming popular for surface modification of fibres. Various chemical- and ultrasound treatments can be used for improving the dyeabiity of the FR fibers. However, the ageing of these treatments can reduce the surface functionality.

Environmental conditions play an important role on fire-fighter heat stress. Therefore, it is necessary to be aware of the difference between requirements of protective clothing in various environmental conditions. The environmental indices are best used as a tool to assist in designing the fire-fighters' protective clothing for various climates. Therefore, research is required to encounter those factors in modeling and designing protective clothing and develop suitable materials, models and testing procedures, which serve both heat protection and comfort of wearer.

Majority of the inherent FR fibers are expensive. Future research should focus on the production of such fibers at more affordable price. The structural modification of aromatic fibers and producing conventional fibers with FR additives can help in this regard. Although some of the FR additives are commercially available, the use of nanotechnology can help to achieve new additives with improved performance.

The number of wears (during fire-fighting) and washes should be recorded for the evaluation of suitability of a FFPPC. Non-destructive test methods such as Raman luminescence, digital image analysis and colourimetry can be used to evaluate the useful service time. However, these methods often result in inconsistent data and wide variability. Hence, designing of appropriate techniques for the evaluation of EOL of the FFPPC will be scope of future research. As the degree of damage to the PPC varies depending on the external factors, an agreement should be established on the relative importance of each factor and performance methods should be developed. Suitable data base can be developed to store the fire incident of a fire-fighter, conditions faced at each fire, maintenances done, laundering cycles and repair information. Standard tests or techniques should also be developed to detect the end of life of a FFPPC or the point at which it should be rejected due to frequent exposure to high heat flux.

The use of nano-materials and nanotechnology can help to achieve improved protection and comfort. These properties can be achieved with lighter weight fabric which can reduce the psychological strain related to heavy fabrics. Nanotechnology can help to use fibre or fabric sensors integrated to the FFPPC for physiological and environmental sensing. The CNB or other new threats can be better overcome by the use of this technology. However, the possible health and environmental hazards related to nanotechnology should be explored before their application. Development of ecofriendly products with easy recyclability is also the area of research now-a-days.

Conclusion

The protective clothing used for fire-fighting is required to shield the fire-fighters from all possible hazards that may be faced during the work and should provide thermo-physiological comfort. These two requirements are always contradictory. The protective clothing is usually heavy, thick with multiple layers, which reduces water vapour permeability and heat exchange across layers from body to the environment. It results the wearer to face heat stress due to the high physical activity and excessive exposure to heat which overloads his metabolic system. Resolving this issue and getting a balance between protection and comfort will always be the area of future research.

Nanotechnology can help to achieve improved protection and comfort, which are always a contradicting paradox. This technology can help to design protective clothing with light weight and less bulk, which can reduce the psychological strain related to heavy fabrics. Nanotechnology can help to use flexible textile sensors integrated to protective clothing to increase their functionality. New threats from chemical, nuclear and biological hazards can be better overcome by the use of this technology. However, the possible health and environmental hazards related to nanotechnology should be explored before their application.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
RN carried out the research, design and drafting the manuscript. SH has been involved in conceiving of the study and participating in its design, draft and revises the manuscript. RP helped in revising the paper and has given the final approval of the version to be published. All authors read and approved the final manuscript.

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