Structural Fire fighting Suits : Futuristic Materials and Designs for Enhanced Comfort

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Abstract

The present work aims to briefly overview the protective clothing being used by the fire fighters during structural fire fighting operations. Future directions towards improving the physiological comfort level offered by the ensemble without compromising on the level of protection against heat loads are also discussed.

Introduction

Structural fire fighting suits belong to the sub-class of protective functional clothing, which are designed with a view to protect our first responders who fight fires during emergency operations. In these scenarios, there is a possibility of the fire fighter being exposed to additional hazards like liquids, pills, and sparks as well [1]. Therefore, a properly designed functional firefighting clothing is required which provides requisite level of protection not only against thermal loads but hazardous liquids, physical and electrical hazards as well. In addition, it should be durable, washable, and most importantly, be comfortable for the wearer.

Figure 1: A schematic representation of the multilayer ensemble of structural firefighting suit.

The entire firefighters’ protective equipment include turnout coat, pants, boots, hood, gloves, self-contained breathing apparatus, and helmet, as governed by the National Fire Protection Association (1971 and 1981 standards. The firefighting suits (as per NFPA1971, EN469 or HII6162-02 or S16890) are a real multi layer ensembles [2], are presentative assembly being shown in Figure 1. The outer layer of the ensemble resist signification when subjected to thermal radiation or short periods of direct flame contact. It also imparts protection against abrasion, cuts and lacerations. Beneath it, exists a moisture barrier layer, which plays a critical role in the suit. Firstly, it prevents the entry of water to the underlying thermal layer; which if enters will displace the air in the thermal barrier, thereby decreasing the level of thermal insulation, subsequently leading to scald injuries. Secondly, the moisture barrier is required to permit the outward movement of perspiration, leading to reduced metabolic heat build-up.
Therefore, the moisture barrier should offer a minimum level of breath ability along with conferring penetration resistance against body fluids and chemicals like battery acids, gasoline, hydraulic fluid etc which keeps the fire-fighter dry and protected. Next in these quence is the thermal barrier layer, the role of which is to impart there quisite level of thermal insulation to the wearer. This layer is usually made up of an on-woven fabric which traps air pockets for enhance dinsulation.

It is to be noted that the expectations from a fire fighter suit are rather contradictory. On one hand, the fire fighter needs to be protected from thermal loads, however, every increasing the thermal in- sulation results in physiological discomfort. Being home other mic, humans need to maintain a stable internal body temperature regard less of the external environment, the inability of which leads to heat strain [3]. Notably, burn injuries experienced by firefighters may reduce to increased number of layers, but can lead to in- crease in incidents related to fatigue, exhaustion, heat strain and fatalities [4].

The efficiency of a firefighter clothing is evaluated primarily on the basis of two criteria: firstly, there striction on the amount of heat load reaching the wearer and secondly, the ease of removal of the metabolic heat produced by the fire fighter himself during the strenuous physical activities. In NFPA1971, these requirements are quantified interms of the Total Heat Loss (THL) and Thermal Protective Performance (TPP) and an ideal suit would be one which exhibits an optimal balance of these two [5]. The former parameter, i.e. THL is a measure of breathability, and is evaluated at the fabric level (garment composite), and the latter, i.e. TPP is an indication of the materials ability to protect against thermal loads, both being inversely proportional. As per NFPA1971, a minimum TPP rating of 35 and a THL of 205W/m² is mandatory for a structural firefighting suit. In the other standards EN469 and IS16890, these are measured in terms of heat transfer (flame exposure and radiant exposure) and water vapour resistance.

It is to be noted that the tests mentioned above are a function of the fabric materials in the three-layer system only, and do not consider additional padding, trim, labels, pockets and other reinforcements. Inpractice, however these suits are wornon the 3-D human form which create additional air gaps between the layers, which further vary at different locations; an issue which is not catered for in the present standards. Also, there is a requirement of a manikin THL benchmark for reducing heat strain, currently, only fabric level test for heat loss values are used in NFPA standards. In the near future, there are primarily two broad domains, where developments in firefighter suit designs can be expected: namely material development and design improvisations.

Innovative materials for futuristic firefighter suits

The present-day material choices for thermal protective clothing include fabrics which are formed from fibers which are flame resistant in view of their inherent structure [6]. Polybenzimidazoles, polybenzoxazoles and melamine formaldehyde based fibers possess hetero cyclic moieties in the main chain, modacrylic fibers contain vinyl/vinylidene chloride groups, polyimides possess a rigid (ladder type) structure and the double bond character of the C-N bond available in them and p-aramids conjugate between the amide groups and the aromatiers resulting in increased chain rigidity and liquid crystalline nature [7]. Polyphenylene sulphide fibers consist of aromatiers linked together by sulphide function ality. All the above-mentioned features help the fibers retain their physical properties at elevated temperatures. It is to be noted that all the commercially available fabrics are prepared from blends of different fibers, each having its own desirable property.

The characteristic property for screening polymers for firefighting application is its susceptibility to combustion, which is quantified in terms of the Limiting Oxygen Index (LOI): the minimum oxygen concentration required for its sustained burning. For all practical purposes, all the flame resistant fibers have an LOI of 27. However, LOI gives only a partial evidence of the materials behaviour towards heat or flames, and there are several other thermal factors which are important in the context of clothing, particularly thermal conductivity and heat capacity.

Future developments in this area would primarily aim at using lighter materials to reduce the overall weight of the fire suit, which will reflect on increased physiological comfort. Recent studies have revealed that introducing nano materials can reduce the flammability of polymers by reducing the heat release rate, increased flame-out and auto-extinguishment properties. The underlying mechanisms is the alteration in the degradation path way, i.e. formation of nano particle reinforced charred protective layers on the surface [8].

The latest developments in this area are in the field of aerogels and phase change materials. The former represents a class of material which are extremely light and offer excellent thermal insulation as well, while the phase change materials can absorb heat energy [9]. The use of shape memory alloys and thermo responsive polymers [10] which can maintain or create insulating layer sorair gap with ingarment systems are also being researched [11]. In view of the extremely low density of the hollow glass micro balloons, along with their low thermal conductivity, the potential of syntactic films can also be explored [12]. However, these ideas are presently in the experimental stages primarily because of the low response of the semimaterials, economic factors and limited durability.

Reducing the fibre dimensions can also alter the performance of fibers under fire scenario. Lately, nano fibrous flame resistant coatings formed by electro spinning process have been reported [13]. It is to be noted that these porous fibers have enormous potential as a breath able moisture barrier layer [14].

The presence of pores can facilitate free movement of the water vapor formed during perspiration, leading to increase develop comfort [15,16].

However, it is to be noted that irrespective of the improvement in breathability, any compromise on the protection level (as indicated-
Design modifications

The most obvious strategy towards improving the comfort level of a firefighter is the introduction of passive or active ventilation. Passive vents are the ones which will always be in place, while active vents are those which remain open under normal conditions but have to be closed during the fire scenario. Other possibilities include alteration in the assembly of the layers, reduction in the air gap volume and system modularity. Recently, as a part of the “Revolutionary Modern Turnoutsuit” project, sponsored by the United States Department of Homeland Security, all these are forementioned design modifications have been explored [17].

It is to be noted that in addition to the basic fibre material, there are a plethora of other factors which affect the behaviour of the fabric under fire scenarios, particularly the weave pattern, fabric direction and the torsion of the constituent yarns [21]. Closed fabric constructions, functional blended fibres, changes in the direction, weight and torsion of the constituent yarns can also lead to improved flame resistance.

Recent developments in the field of nanotechnology permit the integration of flexible textile sensors with the protective clothing to form smart textiles [21,22]. These can be used to record vital physiological data of the firefighters such as respiratory & cardiac activity, blood pressure, body temperature and transmit the same to the base station, which can help in taking informed decisions. The light weight fire fighter gear of the future will have integrated vital-signal sensors as well in do or tracking, which will definitely reduce the number of injuries and fatalities of our fire responders.

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References

1. Guowen S, Faming W (2018) Firefighters’ clothing and equipment. Taylor & Francis, CRC Press, USA.
2. Jacek R, Karolina S, Daria K, Maciej B (2016) Comparison of requirements and directions of development of methods for testing protective clothing for firefighting. Fibers Text East Eur 5(119): 132-136.
3. Mcquerry M, Barker R, Denhartog E (2018) Relationship between novel design modifications and heat stress relief in structural firefighters’ protective clothing. Appl Ergon 70: 260-268.
4. Su Y, Yang J, Song G, Li R, Xiang C, et al. (2018) Development of a numerical model to predict physiological strain of firefighter in fire hazard. Sci Rep 8(1): 3628.
5. Kim JH, Kim DH, Lee JY, Coca A (2017) Relationship between total heat loss and thermal protective performance of firefighter protective clothing and consequent influence on burn injury prediction via flame-engulfment manikin test. Proc Hum Factors Ergon Soc Annu Meet 61(1): 1468-1471.
6. Bajaj P (1992) Flame retardant materials. Bull Mater Sci 15(1): 67-76.
7. Jassal M, Ghosh S (2002) Aramid fibres - An overview. Indian J Fibre Text Res 27(3): 290-306.
8. Nayak R, Houshyar S, Padhye R (2014) Recent trends and future scope in the protection and comfort of firefighters’ personal protective clothing. Fire Sci Rev 3(1): 1-19.
9. Shaid A, Wang L, Padhye R (2015) The thermal protection and comfort properties of aerogel and PCM-coated fabric for firefighter garment. J Ind Text 4(5): 611-625.
10. Mukhopadhyay A, Vinay Kumar M (2008) A review on designing the waterproof breathable fabrics part I: Fundamental principles and designing aspects of breathable fabrics. Journal of Industrial Textiles 37(3): 225-262.
11. Bartkowiak G, Dabrowska A, Greszta A (2020) Development of smart textile materials with shape memory alloys for application in protective clothing. Materials (Basel) 13(3): 689.
12. Ullas AV, Kumar D, Roy PK (2019) Epoxy-glass micro balloon syntactic foams: Rheological optimization of the processing window. Adv Polym Technol.
13. Gallo E, Fan Z, Schartel B, Greiner A (2011) Electrospun nanofiber mats coating-new route to flame retardancy. Polym Adv Technol 22(7): 1205-1210.
14. Yu X, Wu X, Si Y, Wang X, Yu J, et al. (2019) Waterproof and breathable electrospun nanofibrous membranes. Macromol Rapid Commun 40(8): 1-19.
15. Li X, Xiao X, Tian T, Yuan X, Ming L, et al. (2019) Waterproofof-breathable PFTE nano- and microfiber membrane as high efficiency PM2.5 filter. Polymers 11(4): 1-14.
16. Tripathi M, Parthasarathy S, Roy PK (2020) Mechanically robust polyurea nanofibers processed through electrospinning technique. Mater Today Commun 22: 100771.
17. Udayraj, Talukdar P, Das A, Alagirusamy R (2016) Heat and mass transfer through thermal protective clothing - A review. International Journal of Thermal Sciences 106: 32-56.
18. McQuerry M, DenHartog E, Barker R (2017) Evaluating turnout composite layering strategies for reducing thermal burden in structural firefighter protective clothing systems. Text Res J 87(10): 1217-1225.

19. McQuerry M, Barker R, DenHartog E (2018) Functional design and evaluation of structural firefighter turnout suits for improved thermal comfort: Thermal manikin and physiological modelling. Cloth Text Res J 36(3): 165-179.

20. McQuerry M (2018) Effect of structural turnout suit fit on female versus male firefighter range of motion. Appl Ergon 82: 102974.

21. Silva MC, Peixoto J, Fangueiro R, Gasi F, Baruque J (2019) The influence of textile materials on flame resistance ratings of professional uniforms. SN Appl Sci 1(12): 1650.

22. Islam GM, Ali A, Collie S (2020) Textile sensors for wearable applications: A comprehensive review. Cellulose 27(11): 6103-6131.