

**A STUDY ON  
FIREFIGHTERS' PROTECTIVE CLOTHING**

**SUPRIYO CHAKRABORTY**



**DEPARTMENT OF TEXTILE TECHNOLOGY**

**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**OCTOBER 2016**

©Indian Institute of Technology Delhi (IITD), New Delhi, 2016

**A STUDY ON**  
**FIREFIGHTERS' PROTECTIVE CLOTHING**

by  
**SUPRIYO CHAKRABORTY**  
**Department of Textile Technology**

Submitted  
In fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI  
OCTOBER 2016

## CERTIFICATE

This is to certify that the thesis titled “**A study on firefighter’s protective clothing**”, being submitted by **Mr. Supriyo Chakraborty** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by him. He has worked under my guidance and supervision and fulfilled the requirements for the submission of the thesis, which has attained the standard required for a Ph.D. degree of this institute.

The results contained in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any degree or diploma.

Dr. V. K Kothari

Emeritus Professor  
Department of Textile Technology,  
Indian Institute of Technology, Delhi,  
New Delhi - 110016,  
India

## **ACKNOWLEDGEMENTS**

First of all I would like to thank my research supervisor, Prof. V.K. Kothari, who encouraged me to take up this topic for my thesis. He provided continuous guidance, support and encouragement throughout the course of my work. Without his guidance and efforts, my work would not have been completed. It has been a privilege for me to work with him all these years and learn so much from him, in academics as well as in personal life. I am also grateful to Prof. R. Chattopadhyay, Prof. R.S. Rengasamy and Prof. P. Mahajan, my SRC committee members, who helped me by providing many suggestions during my course of study. I am thankful to Prof. P. Talukdar for his suggestion and guidance during various stages of my work. I am also thankful to Dr. J. Sarkar, from whom I learnt fundamental principles of computational fluid dynamics. I am also thankful to Dr. Dipayan Das for his invaluable tips on statistical techniques during my data analysis. I would like to remember Prof. A. Das and Dr. A. Majumdar for encouraging me from time to time during my experimental and analytical works. I am thankful to Prof. R. Chattopadhyay for helping me providing many thoughtful ideas on various aspects of Technology. I like to express thanks to Prof. A. V. Rao of Shivaji University, Kolhapur for providing me laboratory facility at his end to prepare aerogel based composite samples.

I thank the staff members of all the laboratories of the Department of Textile Technology, IIT Delhi, for extending a helping hand whenever needed.

I would like to thank all my research colleagues, Rama Moorthy, J. Kirshnasamy, Mahadev Bar, Rajat Baldua, Udayraj, Vijay Sharma, Ashutosh, Piyali Hatua, Animesh, A. Pisal and many other who helped me a lot in many aspects.

I am indebted to my wife, Lipika without her support nothing would have been possible. I am thankful to my mother and brother for their loving support, and my father for his blessing and well wishes he left for me. I also remember my daughter Diya, for her patience.

Last of all I would like to express thank all the wonderful people I came across and my old friends I met during my stay at the Institute.

Supriyo Chakraborty

## **ABSTRACT**

Firefighters are exposed to various levels of radiant heat and flame hazards. In spite of introduction of different heat resistant fibres and clothing, firefighters receive severe burn injuries. Hence heat protective performance of firefighters' protective clothing is always a critical issue as the life of the person involved is in question. Many studies had been carried to understand and characterise firefighters' and other protective clothing exposed to similar hazards. Various evaluation methodologies have been developed to estimate protective clothing assemblies, designed for protecting the person from a specific sort of hazard. A firefighters' protective clothing usually consists of three clothing layers, typically an outer shell, a thermal liner, and an inner layer. Characteristics of the constituent fibres, constructional features of clothing layers, properties of the yarns used greatly influence heat protective performance.

Radiant heat of various intensities is the main category of thermal hazard faced by a firefighter. The focus of the thesis is to develop an understanding of various physical, dimensional, thermal and optical properties of protective clothing assemblies that affect protection from radiant heat. An instrument for evaluating heat protective performance of clothing assemblies against radiant heat has been developed, based on principles given in ASTM standards. Various commercial woven fabrics made of heat resistant fibres, needle punched nonwoven thermal liners has been used to prepare multilayered assemblies and investigated for radiant heat protection. Heat protective performance of such clothing assemblies has been analysed using statistical techniques and explained from fundamental fabric properties. All the components of a multilayered clothing assembly significantly influence protection. Areal density, air permeability and porosity, optical properties, fibre fineness, bulk density of clothing

layers has been found to be critical. Effect of various constructional properties of clothing assemblies on radiant heat protection has been investigated using woven clothes of varying cover and nonwoven fabrics of different compactness. Empirical relationship for estimated protection time with constructional parameters and heat fluxes was obtained. It was observed that constructional parameter of outer layer cloth most significantly affects protection. Thickness of thermal liners appeared to be another crucial parameter. Protection time has been found to vary nonlinearly with incident heat flux. Effect of preconditioning of protective clothing in different atmospheric conditions, and effect of added water on outer shell in presence and absence of a barrier has been investigated. Moisture in clothing layers and its quantity found to significantly affecting thermal response. Use of a barrier layer was found to be advantageous.

Mathematical modelling can be useful in predicting thermal behaviour of firefighters' clothing assemblies exposed to radiant heat fluxes. A conduction-radiation heat transfer model for firefighters' protective clothing, subjected to high intensity thermal irradiations, has been developed. Experimentally measured physical, thermal and optical properties of multilayered clothing assemblies has been used in the model. Specific heat capacity and thermal conductivity of clothing layers has been considered as function of temperature. Predicted thermal response has been obtained for various incident heat fluxes and clothing assemblies. Predicted thermal behaviour obtained from the numerical solution of the model has been found to be close to the experimentally obtained response. Role of different clothing properties on protection time has been studied from the numerical solution of the model equations. It revealed that fabric reflectance and thickness are the most crucial parameters. Thermal conductivity of fabric and presence of moisture in clothing layers are also found to

affect protection significantly. Effect of air gap between fabric layers has also been studied using the model. Protection time has been found to increase linearly with increasing air gap between fabric layers, both experimentally and from the model.

A new insulating material, namely aerogel-nonwoven composite structures has been studied and their effectiveness in heat protective clothing has been evaluated. Aerogel-nonwoven composites were produced in Laboratory, from two different precursors, using suitable methods of preparation. Aerogel-nonwoven insulation fabric has been found to offer more than 100% protection against radiant heat compared to normal Nomex nonwoven insulations. Higher levels of protection has been achieved at the cost of small increase in fabric areal density.

# Table of Contents

---

	Page No.
Certificate	i
Acknowledgements	iii
Abstract	v
Contents	ix
List of figures	xvii
List of tables	xxi
<b>Chapter I Introduction and Objectives</b>	
1.1 Introduction	1
1.2 Motivation	5
1.3 Objectives	6
<b>Chapter II Review of Literature</b>	
2.1 Introduction	9
2.2 Thermal Hazards and Burn Injuries	11
2.3 Components of the Firefighters' Protective Clothing	12
2.4 Requirements of Firefighters' Protective Clothing	13
2.5 Evaluation Methodologies of Firefighters' Protective Clothing	16
2.5.1 Thermal Protective Performance test (TPP)	17
2.5.2 Total Heat Loss test (THL)	19
2.5.3 Stored Energy Test (SET)	20
2.5.4 Instrumented Manikin test	20
2.6 Heat Sensors and Thermal Protective Performance	21

2.7	Research on Firefighters' Protective Clothing	21
2.7.1	Fibres used in firefighters' protective clothing	22
2.7.2	Characteristics of thermal exposures and protective performance	23
2.7.3	Physical characteristics of heat protective clothing assemblies	24
2.7.4	Moisture in heat protective clothing assemblies and moisture barriers	26
2.7.5	Compression and stored energy	28
2.7.6	Prediction of skin burn injury	28
2.7.6.1	Stoll's second degree burn criterion	28
2.7.6.2	Skin heat transfer model and Henriques' Burn Integral	29
2.7.7	Modeling heat and mass transfer	31
2.7.7.1	Heat transfer through fibrous insulation	31
2.7.7.2	Heat transfer models for firefighters' protective clothing	36
2.8	Some New Approaches for Enhanced Thermal Protection	44
2.9	Summary	46

### **Chapter III Development of an Instrument for Study of Thermal Response of Protective Clothing Assemblies**

3.1	Introduction	49
3.2	Description of the Instrument	49
3.3	Measurement of Heat Flux	53
3.4	Calibration of Heat Flux at different Variac Setting	54
3.5	Results	55
3.5.1	Initial testing	55
3.5.2	Test of repeatability	56
3.6	Observations during use of the Instrument	58

3.7	Testing of the Protective Clothing Materials and their Characterisation	58
3.8	Summary	60
<b>Chapter IV Heat Protective Performance of Clothing Assemblies Exposed to different Radiant Heat Fluxes</b>		
4.1	Introduction	61
4.2	Experimental Work	62
4.2.1	Materials and sample preparation	62
4.2.2	Methods	63
4.2.2.1	Measurement of general fabric parameters	63
4.2.2.2	Measurement of fabric thickness and cover	65
4.2.2.3	Measurement of air permeability	65
4.2.2.4	Measurement of thermal properties	66
4.2.2.5	Measurement of optical properties	67
4.2.3	Estimation of protection time	69
4.3	Results and Discussion	71
4.3.1	Statistical analysis	71
4.3.1.1	Analysis of variance	71
4.3.1.2	Regression model	73
4.3.2	Effect of outer layer fabric	74
4.3.3	Effect fibre fineness of thermal liner	77
4.3.4	Effect of inner layer	78
4.3.5	Effect of heat flux	78
4.4	Summary	80

## **Chapter V Effect of Moisture on Heat Protective Performance of Multilayered Fabric Assemblies**

5.1	Introduction	81
5.2	Materials and Methods	82
5.2.1	Materials	82
5.2.2	Methods	83
5.2.2.1	Measurement of general fabric properties	83
5.2.2.2	Measurement of radiant heat protective performance of clothing assemblies	83
5.2.2.3	Estimation of specific heat with Differential Scanning Calorimeter (DSC)	85
5.3	Results and Discussion	86
5.3.1	Effect of preconditioning	86
5.3.2	Effect of added water on the outer shell fabric	90
5.3.3	Effect of added water on the outer shell fabric with Teflon barrier	92
5.3.4	Effect of fibre fineness of Nomex thermal liner	94
5.4	Summary	95

## **Chapter VI Effect of Fabric Constructional Parameters on Thermal Protective Performance of Clothing Assemblies Exposed to Radiant Heat Fluxes**

6.1	Introduction	97
6.2	Materials and Methods	99
6.2.1	Materials	99
6.2.2	Methods	99
6.2.2.1	Preparation of samples	99
6.2.2.2	Measurement of thickness, areal density and air permeability	99

6.2.2.3	Estimation of protection time against radiant heat	100
6.3	Results and Discussion	102
6.3.1	Effect of pick density	106
6.3.2	Effect of punch density	107
6.3.3	Effect of Heat flux	108
6.4	Summary	111

## **Chapter VII Prediction of Thermal Response and Protective Performance of Multilayered Clothing Assemblies**

7.0	Nomenclature	113
7.1	Introduction	114
7.2	Prediction of Skin Burn Injury	115
7.3	Experimental Setup	116
7.4	Development of the Model	116
7.4.1	Assumptions and features of the model	118
7.4.2	Heat transfer model for clothing assembly	121
7.4.3	Boundary conditions	123
7.5	Measurement of Heat Flux	123
7.6	Fabric Properties	124
7.6.1	Physical properties	124
7.6.1.1	Thickness and density	124
7.6.2	Thermal properties	127
7.6.2.1	Thermal conductivity	127
7.6.2.2	Specific heat capacity	128
7.6.3	Radiative properties	128

7.7	Solution of the Heat Equation	129
7.8	Study of Effect of Air Gaps between Fabrics	132
7.9	Results and Discussion	134
7.10	Summary	147

## **Chapter VIII Comparison of Radiant Heat Protective Performance of Aerogel-Fibrous Nonwoven Composites**

8.1	Introduction	149
8.2	Experimental Work	150
8.2.1	Materials	150
8.2.2	Methods	151
8.2.2.1	Preparation of nonwoven fabric	151
8.2.2.2	Preparation of the TEOS based gel in fibrous structure	151
8.2.2.3	Silylation and ambient pressure drying	151
8.2.2.4	Preparation of the MTMS based gel in fibrous structure	152
8.2.2.5	Supercritical CO <sub>2</sub> drying of the MTMS based gel	152
8.3	Methods of Characterization	154
8.4	Results and Discussion	155
8.4.1	Bulk density and thermal conductivity	158
8.4.2	Radiant heat protective evaluation	163
8.5	Summary	169

## **Chapter IX Conclusions**

## **Chapter X Future Scope of Work**

## **References**

## **Appendices**

<b>A-I</b>	<b>Experimental Protection time for different Fabric Combinations at Various Heat Flux Levels</b>	191
<b>A-II</b>	<b>Computer code for Analysis of Variance</b>	227
<b>A-III</b>	<b>Computer code for Numerical Solution of Heat Equation for Clothing Assemblies</b>	229
<b>Publications</b>		231
<b>Bio-data</b>		233

## List of Figures

<i>Figure no.</i>	<i>Figure Caption</i>	<i>Page no.</i>
2.1	Firefighter deaths by cause of injury.....	10
2.2	Firefighters' exposure conditions.....	12
2.3	General multilayered arrangement of a firefighters' protective clothing.....	15
2.4	Schematic of the NFPA 1971 testing apparatus (all dimensions in mm).....	18
3.1	Schematic diagram of the constructed instrument.....	51
3.2	Rectangular brass plates with opening in the middle for gripping fabric samples.....	51
3.3	The Instrumental setup with sample mounted.....	52
3.4	A fabric sample being exposed to radiant heat.....	52
3.5	ADAM software recording data on computer.....	52
3.6	Typical temperature trace obtained for an arbitrary heat flux incident on copper calorimeter.....	54
3.7	Heat fluxes produced at different Voltage variac setting.....	55
3.8	Typical cumulative thermal energy curves obtained for single layer Conex fabrics exposed at heat flux 20 kW/m <sup>2</sup> .....	57
4.1	Measurement principles of reflectance and transmittance properties with Perkin Elmer UV-Vis-NIR spectrophotometer using integrating sphere.....	68
4.2	Stoll curve and an experimental curve for a combination of fabrics tested at an arbitrary heat intensity.....	71
4.3	Plot of predicted protection time vs experimental protection time.....	75
4.4	Effect of outer layer on protection time (s) at different heat fluxes.....	75
4.5	Spectral reflectance of the fabrics.....	76
4.6	Effect of fibre fineness on protection time (s) at different heat fluxes.....	77
4.7	Comparison of heat protective performance of combinations of fabrics at different heat fluxes.....	79

<b>Figure no.</b>	<b>Figure Caption</b>	<b>Page no.</b>
5.1	Effect of conditioning on heat protective performance of clothing assemblies using two different types of Nomex nonwoven fabrics as thermal liner.....	88
5.2	DSC curve of Nomex nonwoven fabrics.....	89
5.3	Effect of added water on outer layer on heat protective performance using two different types of Nomex nonwoven fabrics as thermal liner.....	91
5.4	Effect of added water on protective heat performance with Teflon film barrier used after outer layer fabric, for two different types of Nomex nonwoven fabrics as thermal liner.....	93
5.5	Diameter of Nomex fibres used in Nonwoven type-1 and -2 at 400X magnification.....	95
6.1	Plot of experimental and predicted protection time(s) .....	104
6.2	Protection time vs. pick density and punch density at different heat flux levels.....	105
6.3	Protection time at different levels of heat flux for single layer non-woven fabrics.....	107
6.4	Plot of protection time for fabric combinations 1, 2 and 3 .....	109
6.5	Interaction of applied heat flux and pick density.....	110
7.1	Schematic representation of heat transfer through multilayered clothing exposed to thermal radiation.....	121
7.2	Change in nonwoven fabric thickness with applied pressure.....	126
7.3	Temperature profile plotted vs thickness (x) and time (t) for a three layered fabric combination exposed to three different heat fluxes.....	131
7.4	Schematic representation of heat transfer in fabric layers with air gap.....	133
7.5	Experimental vs predicted curves at heat flux $20 \text{ kW/m}^2$ .....	135
7.6	Experimental vs predicted curves at heat flux $10 \text{ kW/m}^2$ .....	136
7.7	Experimental vs predicted curves at heat flux $15 \text{ kW/m}^2$ .....	137
7.8	Effect of variation of fabric thickness on the protective performance.....	139
7.9	Effect of variation of fabric thermal conductivity on the protective performance.....	140

<b>Figure no.</b>	<b>Figure Caption</b>	<b>Page no.</b>
7.10	Effect of variation of fabric specific heat capacity on the protective performance.....	141
7.11	Effect of variation of fabric density on the protective performance.....	142
7.12	Effect of variation of fabric reflectance on protective performance.....	143
7.13	Predicted temperature rise is shifted towards right due to presence of moisture.....	145
7.14	Estimated and predicted protection time for fabric combination with different air gap between fabrics layers.....	146
8.1	Preparation of aerogel-nonwoven fabrics using TEOS (Route-1) and MTMS (Route-2) precursors.....	153
8.2	FTIR spectra of the TEOS/TMCS based aerogel nonwoven composites.....	156
8.3	FTIR spectra of the MTMS based aerogel nonwoven composites.....	157
8.4	SEM Images, Nomex fibre, TEOS-TMCS based APD aerogel, MTMS based supercritically dried (SCD) aerogel formed on fibre surfaces.....	159
8.5	Bulk density and Thermal resistance of TEOS:TMCS based aerogel-nonwoven fabrics at different TMCS concentrations.....	160
8.6	Bulk density and Thermal resistance of MTMS based aerogel-nonwoven fabrics at different MeOH:MTMS molar ratios.....	161
8.7	Changes in protection time with increasing concentration of TMCS.....	164
8.8	Changes in protection time with decreasing molar ratio of MeOH:MTMS.....	165
8.9	TGA of Aerogel-fabric insulations compared with parent insulation material.....	168
8.10	Appearance of Aerogel fabric composites after exposure to heat flux of $30 \text{ kW/m}^2$ , (a) and (c) TEOS/TMCS based samples and (b) and (d) are MTMS based samples .....	169

## List of Tables

<i>Table No.</i>	<i>Title</i>	<i>Page No.</i>
3.1	Protection time obtained for the Conex woven fabric	56
3.2	Instruments used for evaluation of fabric properties	59
4.1	Coding of the clothing component used in multilayered fabrics	64
4.2	Properties of the outer layer, thermal liners and inner layer fabrics	66
4.3	Thermal resistance and reflectance of tested fabrics	69
4.4	Protection time (seconds) of different fabric combinations at different heat fluxes	70
4.5	Analysis of Variance table for estimated protection time	72
5.1	Basic physical properties of the fabrics	83
5.2	Protection time (s) of multilayered protective assemblies with different preconditioning, added moisture, and with Teflon barriers	87
6.1	Basic properties of woven and nonwoven fabrics	101
6.2	Process parameters and their levels for factorial design	102
6.3	ANOVA for response surface quadratic model	103
7.1	Physical properties of the heat resistant fabrics used	125
7.2	Radiative properties of the fabrics	125
7.3	Properties of fabrics used in the study of air gap	126
7.4	Effect variation in fabric properties on protective performance	138
8.1	Coding of all aerogel-nonwoven composite fabrics	155
8.2	Thickness, Bulk density and Thermal resistance of aerogel nonwoven composites	162