International Journal of Thermal Sciences 106 (2016) 32–56

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Heat and mass transfer through thermal protective clothing — A review

Udayraj [a], Prabal Talukdar [a,*], Apurba Das [b], Ramasamy Alagirusamy [b]

[a] Department of Mechanical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India
[b] Department of Textile Technology, Indian Institute of Technology Delhi, New Delhi 110016, India

A R T I C L E I N F O

Article history:
Received 4 November 2015
Received in revised form
28 January 2016
Accepted 9 March 2016
Available online 30 March 2016

Keywords:
Thermo-physiological comfort
Heat stress
Flash fire exposure
Radiant exposure
Thermal protective clothing
Thermal protective performance (TPP) and
Second degree skin burn

A B S T R A C T

Thermo-physiological comfort and safety of the people who are working as firefighter, industrial worker, military personnel and race car driver are major concerns. This led to the significant amount of research in the field of thermal protective clothing over the past several years. In this manuscript, a brief review of the research and development in the field of thermal protective clothing is presented and it primarily focusses the studies dealing with the heat and mass transfer aspects in thermal protective clothing. Experimental methods and standards used to analyze the performance of thermal protective clothing are discussed. Advancement in modeling of heat and mass transfer through porous fabrics are highlighted. Heat transfer modeling in air gaps between fabric and human skin as well as bio-heat transfer models used in the performance analysis of thermal protective clothing are also explained. Effect of various parameters like physical and thermo-physical properties of fabrics, air gap, moisture, exposure conditions on protective performance of fabrics are discussed. Recent trends in research in the field of thermal protective clothing are summarized along with suggestions for future research.

Contents

* Corresponding author.
E-mail address: prabal@mech.iitd.ac.in (P. Talukdar).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.03.006

1. Introduction

Safety of industrial workers and firefighters operating under hazardous conditions is a major concern now-a-days. These people encounter various level of heat and flame exposure while performing duty as shown in Table 1 [1]. Exposure to medium or high levels of such heat exposure decreases the performance of the worker as described in the precision study of telegraph key operators conducted by NASA [2]. Moreover, high heat or flame exposure may result in heat stress which sometime may result in life endangering conditions [3]. Sudden cardiac death was the reason for almost half of the total number of firefighters who died while on-duty in the United States. Only half of them had documented their prior heart problem [4,5]. Recently, on 30 June, 2013 a heartbreaking incident took place in Arizona, U. S., where 19 firefighters killed while firefighting. Out of total 65,880 firefighter injuries reported in US in 2013, 45.2% reported during fire ground operations [6]. Approximately 28% of these injuries were either due to contact with heated objects, fire exposure, radiation exposure or extreme weather. Repeated accident and fatalities of firefighters is of concern for governments and researchers as well. Therefore, there is a need to develop better understanding of fire protective clothing. In order to deal with these issues, various standards for thermal protective clothing have been developed over the past few decades by ISO (International Organization for Standardization), NFPA (National Fire Protection Association) and CEN (the European Committee for Standardization). Essential requirements of thermal protective clothing for good efficiency of the worker, firefighter or race driver depends on protection, comfort and other functional properties like tear resistance and abrasion resistance etc. Thermo-physiological comfort of foundry/industrial workers or fire fighters even during normal (non-fire) situation is a concern [7,8]. Hence, development of modern protective clothing is a complicated task because it involves many contradictory requirements [9].

1.1. Skin burn

Burn injuries are often measured in term of degrees of burn. Higher the degree of burn, higher will be the severity of burn. First degree burn is the most common type of burn (like sunburn). Only the outer layer (epidermis) of the skin is affected in this type of burn. Second degree burn usually results in blister and accumulation of fluid. Epidermal and dermal layers (Fig. 1) are affected and healing takes some weeks. Third degree burn is very serious. It results in the damage of regenerative cells and affect basal layer. Healing is not possible naturally.

1.2. Burn prediction methods

In order to predict the second degree burn quantitatively various methods have been proposed. The most cited two are Stoll's criterion and Henriques' burn integral method. Stoll criterion is one of the most widely used methods. Temporal variation of temperature rise of a sensor placed behind fabric sample is recorded. Intersection point of this plot with the Stoll curve defines tolerance time of the fabric sample as shown in Fig. 2. Almost all experimental research found in the literature used this method to convert

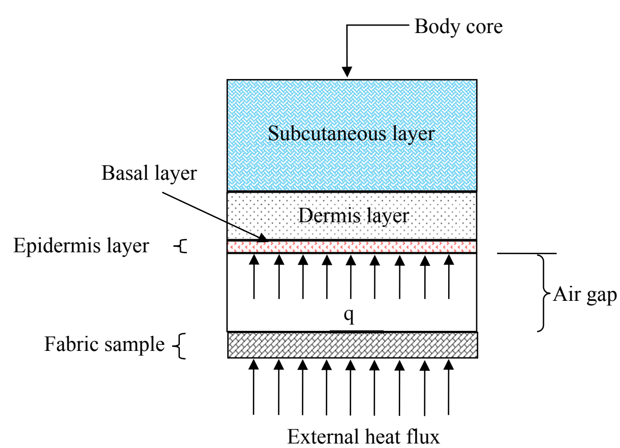

Fig. 1. Schematic of heat transfer through fabric-air gap-skin layer system.

Table 1
Firefighter's thermal environment classification [1].

Exposure	Situations	Air temperature (°C)	Heat flux (kW/m^2)	Tolerance time	Requirement
Routine	Firefighter operating hoses or fighting fire from a distance	60–100	0.83–1.67	10-30 min	No special clothing required
Hazardous	Situation outside a burning room or firefighter ventilating a fire without water	120–300	2–12.5	1-10 min	Turnout uniform is necessary to avoid burn injuries
Emergency	Situations encountered inside a burning building/room by firefighters	300–1200	12–200	5-20 s	Special thermal protective clothing required