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Numerical investigation of the effect of air gap orientations and heterogeneous air gap in thermal protective clothing on skin burn

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ABSTRACT

Numerical model for heat transfer through air gap in thermal protective clothing was coupled with bio-heat transfer model for multi-layer human skin. Coupled CFD-radiation heat transfer model was used for heat transfer through air gap and Pennes' bio-heat transfer model was used for heat transfer through human skin. First and second degree skin burn times were calculated using Henriques' burn integral. Effect of air gap width and air gap orientations were analyzed on heat transfer through air gap and skin burn injuries. Significant impact of air gap width and air gap orientations were observed in first and second degree burn times. First and second degree burn times and hence the thermal protection were found to be higher in case of vertical air gap orientations as compared to horizontal air gap orientations. Air gap orientation influences the thermal protection more at higher air gap widths. Analysis were also performed for determining outcome of heterogeneous air gaps on heat transfer through air gap and protective performance. Heterogeneous air gap cases results in more heat transfer and lower thermal protection as compared to homogeneous air gap cases for both the air gap orientations. Further, effect of fold aspect ratio was also analyzed on first and second degree burn times in case of the heterogeneous air gap.

1. Introduction

Thermal protective clothing is essential for firefighters, industrial furnace operators and military personnel as they are usually exposed to extreme hot environments [1]. The external environment can be flame exposure, radiant heat exposure or combined convective/radiant heat exposure. Thermal protective clothing acts as a thermal barrier between external environment and human body by avoiding direct contact of hot environment with the body as shown in Fig. 1. Thermal protective clothing is a multi-layer arrangement with outer shell, moisture barrier and inner liner. Air gap present between clothing and body as well as air gap present in between various fabric layers positively affect protective performance of clothing. Fabrics used for thermal protective clothing does not melt or drip and maintains its mechanical and insulative properties even at high temperatures encountered during various heat exposures. It is still not possible to avoid skin burn injuries for more than few seconds even with the existing thermal protective clothing as far as high intensity exposures are concerned. So, in order to develop better understanding of heat transfer through clothing and improving thermal protective performance of clothing, significant research has been conducted on thermal protective clothing over the past few decades. Full scale manikin facilities were developed to analyze protective performance of ensembles according to ISO 13506. Computational fluid dynamics (CFD) analysis were also performed for full scale flame manikins [2]. Bench top tests are available [3,4] to experimentally analyze problem of heat transfer through fabrics used in thermal protective clothing, shown in Fig. 1. These bench top tests are relatively simple and convenient as compared to full scale tests. Effect of various parameters related to fabrics like fabric thickness and density [5], fabric structure [6] and moisture present in the fabrics [7–10] were analyzed.

As mentioned above and shown in Fig. 1 that apart from fabrics, thermal protective clothing offers additional thermal protection by incorporating air gap between clothing and body. Hence, it is equally important to analyze and understand heat transfer through air gap properly to be able to understand heat transfer through thermal protective clothing and skin burn accurately. Various

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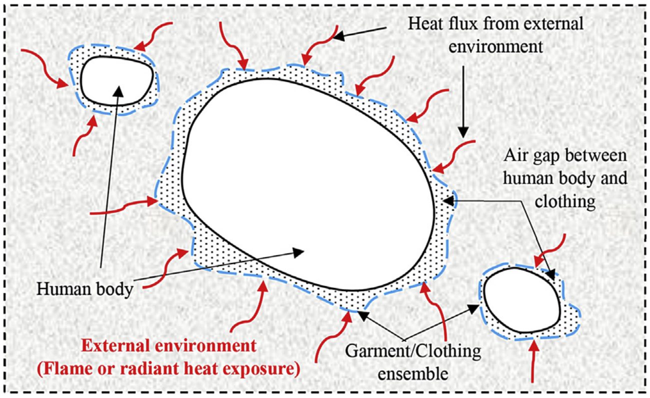

Fig. 1. Heat transfer through clothing and air gap at a cross-section of upper torso of human body.

experimental studies are available where effect of air gap widths on heat transfer was analyzed with dry [11] and wet [7] fabric samples using bench top tests. One of the initial attempt to model heat transfer through air gap was by Torvi [11] and Torvi and Dale [12]. Simple correlation was used to deal with convective heat transfer across the air gap where convection and radiation across air gap were considered to be uncoupled. Above simplified model was modified later [13] to take into account temperature variation along the plane of fabric observed during experimental measurement. Accordingly, treatment of radiation and convection heat transfer were modified to incorporate local temperature variation. Ghazy and Bergstrom [14] analyzed one-dimensional coupled conduction-radiation heat transfer through air gap and neglected convection contribution. A more involved three-dimensional numerical model was later developed by Talukdar et al. [15] where coupled conduction, convection and radiation was considered. Accuracy of the model was not good at higher air gap width and it was improved by Udayraj et al. [16] by treating the natural convection across the air gap in a better way. They [16] developed a coupled CFD-radiation model, accuracy of which was found to be far better than the previous model [15] for various air gap widths.

It can be observed from the literature that the extent of air gap at various locations in the body depends on various factors like body posture, body movement, fabric drapability, garment fit, and garment type [17,18]. In actual conditions, air gap available between clothing and body is not uniform as shown in Fig. 1 also. However, in all the previous studies on heat transfer through air gap mentioned above, air gap was considered to be homogeneous or uniform. Also, only horizontal air gaps were considered in all of the above studies. Even the bench top tests based on ISO 9151, ASTM D 4108 and ISO 17492, ASTM F 2700, ASTM F 2703 consider only homogeneous and horizontal orientation of air gap. Only very recently, Udayraj et al. [16] analyzed effect of horizontal and vertical air gaps on heat transfer through air gap and fluid motion in air gap. Even in this study [16] also, only homogeneous air gap was considered. Although a study [17] is available where effect of heterogeneous or wavy air gap was analyzed experimentally, but this study was not at all related to thermal protective clothing.

So, it is clear that the heterogeneous air gap and vertically oriented air gap are the two conditions which exists in most of the practical situations. It is important to consider these two kind of air gaps while analyzing heat transfer through thermal protective clothing. No study is available in the literature where effect of heterogeneous air gap, which is more close to reality, were analyzed on heat transfer through air gap. Hence, in the present study, effect of heterogeneous air gap was analyzed on heat transfer through air gap and skin burn injuries for the first time. Analysis was carried out for both the horizontal and vertical air gap orientations.

2. Problem description

Present work deals with heat transfer through thermal protective clothing and determining second degree burn time. The problem of heat transfer through thermal protective clothing can be represented with the help of schematic shown in Fig. 2. It can be observed that the problem can be divided into three major sub-problems: heat transfer through fabric, heat transfer through air gap and heat transfer through human skin. Present study focusses mainly on heat transfer through the air gap and human skin. Regions of interest here (air gap and human skin layers) are shown with the dotted enclosure in Fig. 2.

Heat transfer through air gap was analyzed first considering coupled CFD-radiation heat transfer. Air gap was modeled as three-dimensional enclosure with sensor at the top and shim stock at the bottom as shown in Fig. 3 (a). Based on this analysis, variation of total heat flux reached at the sensor with time was obtained. This total heat flux was then applied at the boundary of multi-layer human skin as shown in Fig. 3 (b). Heat transfer through skin layers was analyzed using the Pennes bio-heat equation. With the determined temperature distribution across various skin layers, second degree burn time was then calculated using the Henriques' burn integral.

3. Numerical modeling

Numerical models were developed for heat transfer through air gap and multi-layer human skin. Based on the heat transfer analysis, second degree burn time was determined.

3.1. Heat transfer through air gap

Air gap between fabric and skin was considered to be a three-dimensional enclosure as shown in Fig. 3 (a). Bottom boundary of the air gap enclosure (computational domain) was actually a shim stock (fabric) and a copper calorimeter sensor was mounted at the top boundary as per ISO 9151. Heat transfer through air gap was analyzed using a recently developed coupled conduction, convection and radiation numerical model [16]. The governing conservation equations, Eq. (1)-Eq. (5), for a three-dimensional, unsteady, laminar and incompressible flow were solved using commercial CFD solver Ansys FLUENT.

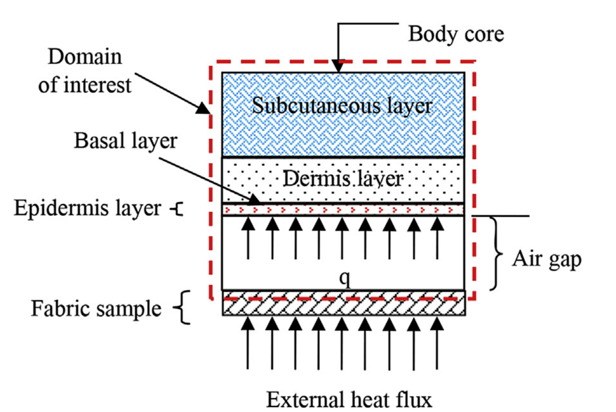

Fig. 2. Schematic diagram showing fabric-air gap-skin system in a typical thermal protective clothing and region of interest for the present problem.