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Numerical modeling of heat transfer and fluid motion in air gap between clothing and human body: Effect of air gap orientation and body movement

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

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ABSTRACT

Air gap available between the clothing and human body provides significant thermal insulation and hence enhances the protective performance of clothing. A numerical model of fluid motion and heat transfer through the air gap is proposed in this work. The most realistic and detailed model considered in this work shows better accuracy than the previous models and brings several new insights to the combined heat transfer phenomena. Effect of horizontal and vertical air gap orientations on sensor temperature rise, heat flux, thermal protection and fluid flow behavior are analyzed. Results shows that thermal protection with the vertical air gap orientation is significantly better than the protection offered by the horizontal air gap orientation and the difference increases as the air gap width increases. Dynamic mesh technique is used in order to investigate the effect of dynamic air gap which results because of the body movement during heat exposure. Body movement is considered to be such that variation of the air gap with time is sinusoidal. Effect of motion frequency and average air gap width are also studied. Significant difference in convective and total heat flux as well as flow pattern is observed for cases with dynamically varying air gap.

1. Introduction

Firefighters and furnace operators working in industries are usually subjected to high heat exposures. Heat exposures may involve radiative, convective (flame) or combined convective/radiant heat flux conditions. Exposure heat flux can vary in the range of 1.0 kW/m^2 to as high as 200 kW/m^2 [1]. It is essential under such circumstances that the firefighters or industrial operators working in such high heat exposure conditions should wear special thermal protective clothing. These thermal protective clothing acts as thermal barriers and helps in avoiding the thermal injuries. It is well known that there exists some air gaps between thermal protective clothing and human body. Air gap between body and clothing varies from location to location within the body. This air gap not only depends on location and posture of the body but also on the clothing fit [2]. Heat from the external exposures passes through clothing and air gap to reach the body. In order to analyze the typical problem of heat transfer through fabric-air gap system under high heat exposure conditions, various thermal protective performance (TPP) tests were developed. One such TPP test which is widely used to analyze protective performance of fabrics under flame exposure is shown in Fig. 1. In this bench top test, propane gas is used to obtain flame exposure and intensity of heat exposure can be fixed as per requirement by adjusting gas flow rate. The fabric/fabric assembly to be tested is placed over the specimen holder as shown in Fig. 1 and desired air gap between fabric and sensor is maintained. This air gap maintained in the bench top test represents the air space usually available between clothing and human body. A copper calorimeter sensor is used in place of human skin and temperature rise of the sensor is monitored during the exposure. This temperature rise together with Stoll's curve is used to determine skin tolerance time or thermal protective performance of fabrics. Thermal protective clothing avoids direct contact of external environment (heat or fire) from the body apart from providing thermal resistance with the help of multi-layer fabric assembly. Air gap available between clothing and body provides additional and significant amount of thermal resistance as air is a low thermal conductivity fluid. In this way, air gap is one of the crucial factor which plays an important role in deciding the thermal protective performance offered by the clothing ensemble. The present study,

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

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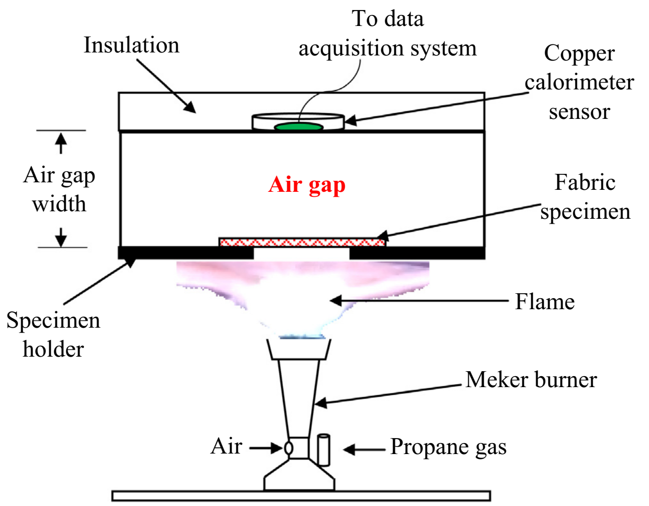

Fig. 1. Schematic of experimental setup used in thermal protective performance (TPP) test (flame exposure).

therefore, focuses on the analysis of heat transfer through the air gap.

Heat transfer through the air gap has been studied by various researchers in the past which includes both experimental and numerical analysis. A numerical model was developed by Torvi [3] for fabric-air gap system. Heat transfer through air gap was considered to be by conduction/convection and radiation. These modes of heat transfer are considered to be uncoupled and both convection and radiation were treated in a very simplified manner. Air gap was simply considered to be a slab with an effective thermal conductivity which was calculated by summing up contributions due to radiation and convection [3,4]. Effect of air gap width on time to exceed the Stoll's criterion was analyzed experimentally and numerically for 82 ± 2 kW/m^2 flame exposure. Significant difference in between the experimental and numerical results were observed. Sawcyn [5] later conducted experiments for 80 ± 2 kW/m^2 flame exposure and measured shim stock surface temperature using thermocouples. It was found that temperature distribution in the shim stock varies as concentric squares. Based on the obtained temperature distribution at the shim stock surface, an improved numerical model was developed. This numerical model treated radiation and convective heat transfer through the air gap in a much better way as compared to previously developed heat transfer model by Torvi [3,4]. Radiation and convection were treated in a more localized manner and area weighted average of surface temperature was used to determine convective heat transfer across the air gap enclosure [6].

A new numerical model was introduced later [7] for fabric-air gap-skin system wherein heat transfer through fabric and skin were treated in the same manner as in previous studies [3,4]. However, heat transfer through air gap was considered in a different way and coupled conduction-radiation heat transfer through air gap was considered as compared to uncoupled approach used earlier [3,4,6]. Finite volume method (FVM) was used to solve the radiative transfer equation (RTE) and energy equations. This model was later extended further to analyze effect of dynamic air gap on heat transfer through fabric-air gap-skin system [8]. This model developed and used by Ghazy and Bergstrom [7,8] solved energy equation dealing with conduction-radiation along with the RTE in the air gap. However, convective heat transfer through the air gap was ignored in these studies which can be significant in case of higher air gap [9]. Convective heat transfer through the air gap was considered later in the numerical modeling by Talukdar et al. [10] in a sophisticated manner. Full Navier-Stokes equations and energy equation considering coupled conduction, convection and radiation were solved along with the RTE. Here also, the FVM was used to discretize the governing equation. Numerical results obtained from the study were compared with the experimental results of the previous studies [5] and significant difference between the two were observed especially at higher air gap widths. They used the Boussinesq approximation together with the temperature dependent properties. However, in this problem, there exist a large temperature difference and the Boussinesq approximation is not very accurate for such large temperature difference [11].

It can be observed from the above studies that none of the studies deals with heat transfer through the air gap accurately. There is only one study [10] which considers coupled conduction, convection and radiation inside the air gap. However, accuracy of their model was not good especially at higher air gap widths. In the present study, an improved coupled CFD and radiation model for heat transfer through the air gap is proposed.

It is to be noticed that all the previous studies considered the air gap between the fabric and human body to be horizontal as specified in ISO 9151 [12] and ASTM 4108 [13]. However, in actual situations, orientation of the air gap can be horizontal or vertical depending upon the location on the body and posture of the wearer. In most of the practical and real life situations, orientation of this air gap is vertical. None of the previous studies analyzed this vertical orientation of the air gap and consequent characteristics of heat transfer behavior in case of the vertical orientation as compared to the horizontal orientation. Hence, for the first time, effect of the two orientations (horizontal and vertical) of the air gap on heat transfer and fluid flow motion are analyzed in the present study.

All the previous studies discussed above considered stationary or fixed air gap. In actual conditions, people wearing thermal protective clothing has to undergo lot of physical activities during fire extinguishing or rescuing operations. Depending upon the garment size [14], different postures [15] or body motions [16] like walking, running, crouching, crawling and bending, etc. there can be different air gaps at different locations in the body and even dynamically changing air gap at the same location. Air gap width changes during the heat exposures not only due to body movement but also due to thermal shrinkage of fabrics [14]. It has been found from the literature that there exist only very few studies [8,17] which considered the changes in the air gap during the heat exposures while analyzing heat transfer through the air gap. Xin et al. [17] experimentally analyzed the effect of dynamic air gap on protective performance for various fabric samples. An existing bench top test where air gap remains constant was modified so that the dynamic air gap conditions can be simulated. Experiments were conducted for 84 ± 2 kW/m^2 combined convective/radiant (50/50) exposure and three different frequencies of the sinusoidal air gap width variations. They found that the effect of frequency of air gap width variation on the sensor temperature rise was not significant. Ghazy and Bergstrom [8] analyzed effect of frequency and amplitude of sinusoidal air gap width variation on protective performance of clothing with the help of a numerical model [7]. It was observed that the TPP of clothing increases as the frequency of cyclic variation of air gap increases. On the contrary, protective performance of clothing reduces as the amplitude of cyclic variation of the air gap increases. It is obvious that during dynamic variation of air gap, the distance between clothing and body changes continuously. This not only causes change in radiative heat transfer across the air gap but also results in significantly different convective heat transfer as there will be fluid motion caused due to dynamic variation of air gap. None of the previous studies [8,17] analyzed the changes in flow patterns and convective heat transfer