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Effect of air gaps characteristics on thermal protective performance of firefighters' clothing

A review

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Abstract

Purpose – The purpose of this paper is to provide the details of developments to research works in the distribution characteristics of the air gaps within firefighters' clothing and research methods to evaluate the effect of air gaps on the thermal protective performance of firefighters' clothing.

Design/methodology/approach – In this paper, the distribution of air gaps within firefighters' clothing was first analyzed, and the air gaps characteristics were summarized as thickness, location, heterogeneity, orientation and dynamics. Then, the evaluation of the air gap on the thermal protective performance of fighters' clothing was reviewed for both experimental and numerical studies.

Findings – The air gaps within clothing layers and between clothing and skin play an important role in determining the thermal protective performance of firefighters' protective clothing. It is obvious that research works on the effects of actual air gaps entrapped in firefighters' clothing on thermal protection are comparatively few in number, primarily focusing on static and uniform air gaps at the fabric level. Further studies should be conducted to define the characteristic of air gap, deepen the understand of mechanism of heat transfer and numerically simulate the 3D dynamic heat transfer in clothing to improve the evaluation of thermal protective performance provided by the firefighters' clothing.

Practical implications – Air gaps within thermal protective clothing play a crucial role in the protective performance of clothing and provide an efficient way to provide fire-fighting occupational safety. To accurately characterize the distribution of air gaps in firefighters' clothing under high heat exposure, the paper will provide guidelines for clothing engineers to design clothing for fighters and optimize the clothing performance.

Originality/value – This paper is offered as a concise reference for researchers' further research in the area of the effect of air gaps within firefighters' clothing under thermal exposure.

Keywords Numerical simulation, Air gaps, Distribution characteristics, Firefighters' clothing, Thermal protective performance

Paper type General review

1. Introduction

Firefighters often encounter flames, high air temperatures and radiant heat in fire-fighting operation (Lawson, 1997). According to official statistics of National Fire Protection Association, there was approximately 1,345,500 fire accidents in 2015, causing 3,280 deaths and 15,700 burn

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injuries (Haynes and Molis, 2015). Firefighters' clothing is a critical equipment to minimize skin injuries and ensure the firefighters' safety (Torvi and Hadjisophocleous, 1999). When exposed to heat, the flame-retardant fabric layers and air gaps between the layers provide thermal resistance to heat transfer from hazardous environments to human skin (Udayraj *et al.*, 2016).

The thermal protection provided by clothing has been extensively investigated over the past several years (Udayraj *et al.*, 2016). The evaluation of thermal protective performance (TPP) of clothing is typically based on the total energy that transfers to the skin through the fabrics and the air gap that causes burn injuries (Ghazy and Bergstrom, 2010). Several researchers have examined many factors involved in affecting the TPP of fabrics. These factors can be classified as external heat flux, fabrics used, air gap available between fabric and skin and heat transfer in skin. Among these parameters, it has been proved that the TPP of clothing can be affected by the level of heat flux (Fu *et al.*, 2014a, b; Eni, 2005; Song, Cao and Gholamreza, 2011; Udayraj *et al.*, 2014; Benisek and Phillips, 1981; Song, Paskaluk, Sati, Crown, Doug Dale and Ackerman, 2011), fabric thickness and density (Song, Paskaluk, Sati, Crown, Doug Dale and Ackerman, 2011; Day and Sturgeon, 1987; Yoo *et al.*, 2000; Kutlu and Cireli, 2005), moisture contained within fabrics (Lee and Barker, 1986; Lawson *et al.*, 2004; Barker *et al.*, 2006; Song, Paskaluk, Sati, Crown, Doug Dale and Ackerman, 2011), as well as the stored energy. Specially, previous studies, including the bench-scale tests (Lu *et al.*, 2012) and flame-manikin tests (Song, 2007; Mah and Song, 2010b) showed that air gaps played an important role in thermal protection.

The existence of the air gaps within the firefighters' clothing greatly improve the TPP of clothing, and accordingly attract the scholars' attention. The studies on the distribution characteristics of the air gap, the influence rules of the air gap on the thermal protection, as well as the mechanism of heat transfer in the air gap have been addressed extensively in the literature by many researchers. The mode of heat transfer within the air gap can be radiation, conduction or convection. These modes of heat transfer between the fabric and the skin depend on the thickness of the air gap (Chianta and Munroe, 1964). The air has good thermal insulation whose thermal conductivity is lower than textiles (Frackiewicz-Kaczmarek *et al.*, 2015). When there was 6.4 mm air gap between fabric and sensor in TPP test, thermal protection of the candidate fabrics was significantly improved (Wang *et al.*, 2015). Heat conduction and radiation are the primary modes of heat transfer within smaller air gap, and the thermal insulation increases as the air gap thickness increases (Benisek and Phillips, 1981). Convection heat transfer can occur with the further increase of air gap thickness (Sawcyn, 2003; Talukdar *et al.*, 2010), the insulating effect of air gap will be weakened (Sawcyn and Torvi, 2009; Song *et al.*, 2008; Torvi and Threlfall, 2006). Due to the complex geometry of human body and specific fabric properties, the air gap entrapped in multi-layer fabrics and over human body is unevenly distributed (Song, 2007; Mah and Song, 2010a).

However, certain limitations exist in the characterization of this air gap. The limitations include, for example, the mean thickness of air gap was calculated with selected points or discrete points of the cross-section of dressed human body (Song, 2007; Wang *et al.*, 2006; Xu and Zhang, 2009; Kim *et al.*, 2002). In view of the complexity of air gap size and distribution, simulating the real shape of air gap is difficult to operate in the practical experiment. Most researchers tended to investigate the effects of air gap on TPP by numerical simulation. However, most of the current mathematical models make assumption that either the air gap is evenly distributed over the thermal sensor or the fabric is in complete contact with the sensor. It should be noted that the size of air gap varies with different body sections (Song, 2007) and the air gap is changing dynamically instead of fixed or static during exposed to the heat (Ghazy, 2014a).

In this paper, the thickness, location, orientation, dynamic and heterogeneity were summarized as the characteristics of air gap within firefighters' clothing. The studies on the effects of these characteristics on the TPP were experimentally and numerically reviewed.

Moreover, the future trend of development in the characteristics of air gap entrapped within thermal protective ensembles was concluded. The research will help understand the air gap effects and its association with thermal protection, and provide guidelines for clothing engineers to improve the TPP of clothing.

2. Distribution of air gap

In the environment-clothing-human system, the energy emitted from the heat source transfers through the multi-layer fabrics and the insulating air gap to the human skin. The process of heat transfer is shown in Figure 1.

For a single-layer clothing (Ghazy and Bergstrom, 2010), the air gap only exists between clothing and human skin. Yet, air gaps are within outer shell-moisture barrier (Figure 1, Position 1), moisture barrier-thermal liner (Figure 1, Positon 2) and inner layer-human skin (Figure 1, Position 3) for multi-layer fabric system consisting of outer shell, moisture barrier, thermal liner and comfortable layer (Ghazy and Bergstrom, 2012). The two layers of thermal liner and comfortable inner are usually quilted together, thus the air gap between them is ignored.

The increase of air gap thickness could provide better thermal insulation as the thermal conductivity of the static air is lower than the conventional fire-retardant fibers (Frackiewicz-Kaczmarek *et al.*, 2015). Nevertheless, the insulating effect of the air gap will be weakened if the size of the space is large enough that the natural convection occurs (Torvi *et al.*, 1999). The complexity of the body shape and the properties of the fabrics make the air gap non-uniform (Song, 2007). The location, thickness and heterogeneity can be defined as the characteristics of the air gap.

To simulate the realistic condition where a gap exists between the clothing and the skin, the testing standards (ASTM F2700, 2008; ASTM F2703, 2008), regulate that the air gap between the tested fabric and the sensor should be 6.4 mm. However, in most of standard bench-top tests (ASTM F2700, 2008; ASTM F2703, 2008; ISO 17492, 2003; ISO 9151, 1995), the specimens are horizontally placed over the heat with the horizontal and homogeneous air gaps, whereas the orientation of the air gap can be horizontal, vertical and inclined depending upon the position on the body and the posture of the wearer in actual conditions (Mayor *et al.*, 2015). Thus, when evaluating TPP of clothing, the realism of air gap direction should be concerned.

In an actual situation, the firefighters undergo constant physical activities during extinguishing the flames or rescuing operations which lead to a dynamic change to the air

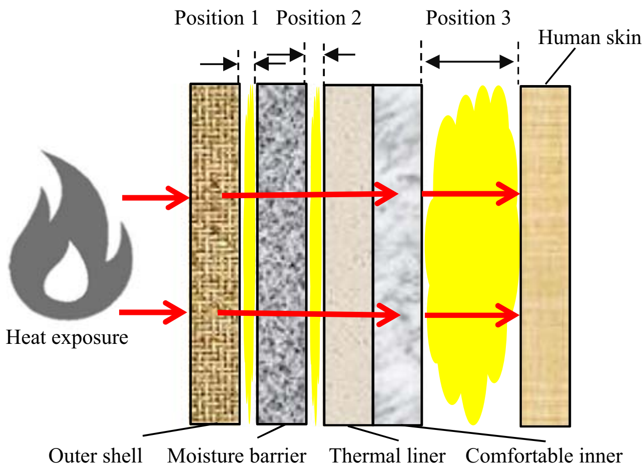


Figure 1.
Heat transfer process of firefighters' clothing

gap (Li *et al.*, 2011; Choi *et al.*, 2014). In addition, the thermal shrinkage of the fabrics also results in air gap changes during the heat exposure (Ghazy, 2014a).

Therefore, the characteristics of the air gap can be summarized as three classes which include five parts such as thickness, location, heterogeneity, orientation and dynamics based on the characteristics of its distribution mentioned above, as shown in Figure 2.

3. Measurement and performance evaluation of air gap

Figure 3 is drawn to illustrate the experimental method used to evaluate the effects of air gap characteristics on the TPP. The experimental study follows the process that first imitate/extract the characteristics of air gap in the fabric/clothing level, and then perform bench-scale/full-scale of TPP test.

3.1 Measurement of air gap

As air gaps entrapped in thermal protective clothing play an important role in heat transfer, quantifying the size and distribution of air gaps in thermal protection clothing is essential.

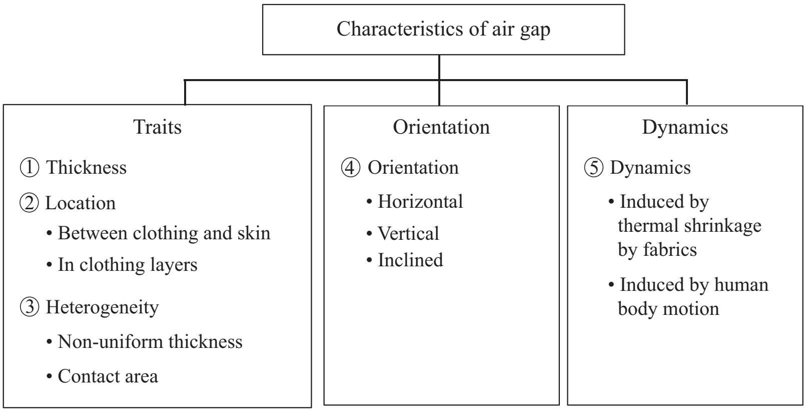


Figure 2. Classification of air gap characteristics

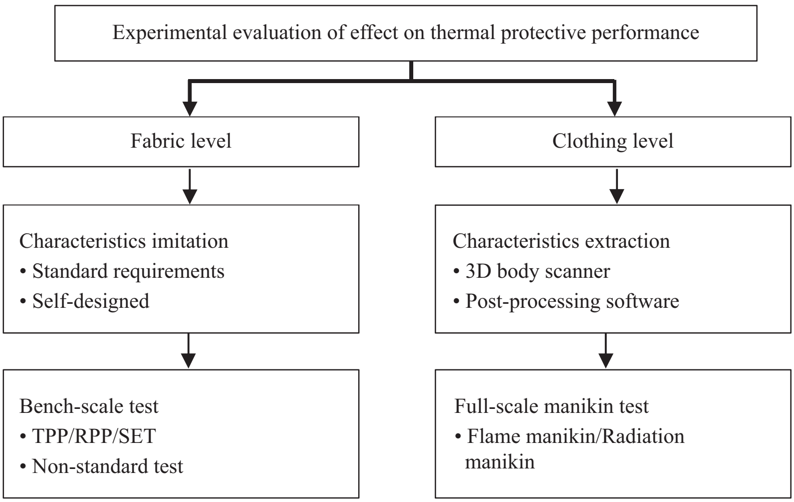


Figure 3. Experimental evaluation of the air gap effects

Traditionally, a vacuum suit method was developed by Crockford and Rosenblum (1974) and further in the works of Birnbaum and Crockford (1978) and Sullivan *et al.* (2007), using an airtight suit to measure the quantity of air between the clothing and the skin. With this method, the total air volume trapped between clothing and body can be determined, while the measurement of the air volumes in different body parts or the air gap thickness in various body cross-sections cannot be determined. Later, the circumference model technique was introduced by Lotens and Havenith (1991) to estimate the air volume, assuming the body as a series of cylinders. However, the precision of its calculation is relatively lower, because of neglecting the concave and convex curvatures of the human body.

In recent years, 3D body scanning technology, which provide accurate representations of the surface of the human body, has become a main method for visualizing and quantifying the air gap between the clothing and the wearer. Generally, the quantization of air gaps is based on the scanning data obtained by various 3D body scanners, following the post-processing of the data using the reverse engineering software. The process of the measurement of air gap with 3D scanning technique is shown in Figure 4.

A 3D whole body digitizer was employed by Kim *et al.* (2002) to determine the local and global distributions of air gap in protective clothing systems dressed on a thermal manikin. Song (2007) determined the air gap size and distribution of single-layer protective clothing using a 3D body scanning technique. A procedure using a 3D body scanner to measure the size and distribution of air gap between a garment and a female manikin was introduced to investigate the air gap on thermal protection against flash fire (Mah and Song, 2010a, b). However, the Vitus Smart 3D body scanner in their studies must work in a fixed area, and thus it cannot be guaranteed that the air gap distribution is absolutely the same while taking a scan. Instead of measuring the air gap by the difference of two vectors originated from the centroid of base scan with the same direction (Kim *et al.*, 2002; Mah and Song, 2010b), Lu *et al.* developed a novel method using the principle of minimum distance to determine the air gap, with Vitus Smart 3D body scanner. Psikuta *et al.* (2015) compared two 3D scanners: Vitus XXL and Artec MHT, and found that the former was limited to a fixed field, while the latter had confined measuring area. In order to conduct a field measurement eliminating the error caused by the move of the scanning object, Wang *et al.* (2016) utilized a portable 3D body scanner, which was mounted into the flame chamber to capture the 3D images of the nude and clothed manikin before and after the flash fire exposure.

The current 3D body scanning technique is restricted to the air gap measurement of single-layer clothing. As the air gaps also exist in clothing layers for multi-layer protective garments, it is in urgent need of the representation of the multi-air gaps. Besides, it is

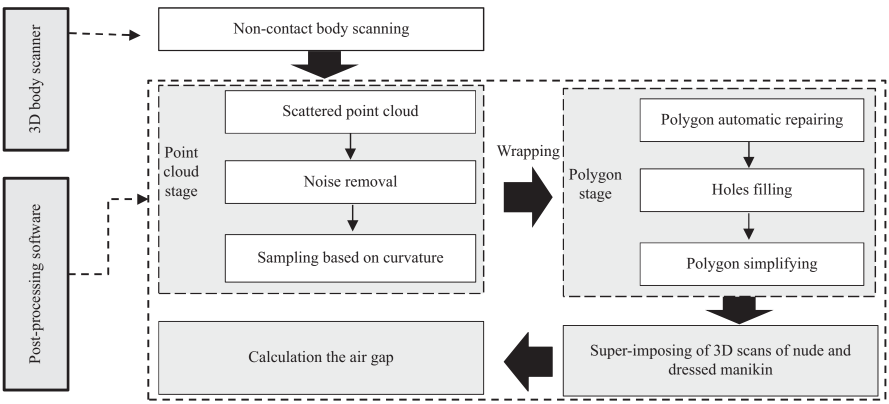


Figure 4.
Flow chart of measurement of air gap with 3D scanning technique

required to improve the data post-processing. For the post-processing of the scanning data, the corresponding software used with 3D scanner may result in the inaccuracy of air gap determination. That is due to the most of those software is designed for the near-parallel surfaces instead of such irregular gap shapes (Psikuta *et al.*, 2015). A study had shown some inaccuracy in determination of the air gap for the highly concaved lumbus area (Psikuta *et al.*, 2012).

3.2 Experimental evaluation of air gap

In most standard bench-top tests, fabric is located horizontally over the heat source with the horizontal air gap as specified in standard test methods (ASTM F2700, 2008; ASTM F2703, 2008; ISO 9151, 1995; ISO 17492, 2003) (Table I). However, the orientation of the air gap between a garment and a human are almost always vertical in actual dressed conditions. Although the fabric sampling is placed vertically in radiant protective performance and Stored Energy Test testers, the corresponding standards (ASTM F1939, 2015; ASTM F2702, 2015; ISO 6942, 2002; ASTMF2731, 2011) ignore the air-spaced configuration.

4. Numerical simulation of heat transfer in air gap

Whereas it has proved to be difficult to accurately manipulate the characteristics of air gap in either small-scale top tests or full-scale manikin tests for thermal protection of firefighter suits, investigating the heat transfer in the air gap by numerical simulation is an efficient and convenient way. Table II shows the typical numerical studies in heat transfer through air gap.

4.1 Modeling of static air gap

4.1.1 Choice of heat transfer model. The different heat transfer modes through the air gap mainly include conduction, convection and radiation depending on the thickness of air gap,

Standard	Heat flux (kW/m^2)	Orientation	Specified air gap between specimen and sensor
Direct flame exposure			
ISO 9151-95 (ISO 9151, 1995)	80 ± 4	Horizontal	0 mm
ASTM D 4108-87 (ASTM D4108, 1987)	83	Horizontal	0 mm or 6.4 mm
Radiant heat exposure			
ASTM F1939-15 (ASTM F1939, 2015)	Method A: 21 Method B: 84	Vertical	0 mm
ASTM F2702-15 (ASTM F2702, 2015)	Method A: 21 Method B: 84	Vertical	0 mm
ASTM F2731-11 (ASTMF2731, 2011)	8.5 ± 0.5	Vertical	0 mm
ISO 6942-02 (ISO 6942, 2002)	Low level: 5 and 10 Medium level: 20 and 40 High level: 8	Vertical	0 mm
Combined convective and radiant heat exposure			
ASTM F2700-08 (ASTM F2700, 2008)	84 ± 2 (50% convective and 50% radiative)	Horizontal	0 mm or 6.4 mm
ASTM F2703-13 (ASTM F2703, 2008)	84 ± 2 (50% convective and 50% radiative)	Horizontal	0 mm or 6.4 mm
ISO17492-03 (ISO 17492, 2003)	80 (50% convective and 50% radiative)	Horizontal	0 mm or 6.4 mm

Table I. Air gap specified in various standard bench-top tests

Representative researches	Design for	Equation dimension	Treatment of heat transfer	Description
Static air gap				
Torvi (1997)	Horizontal air gap; 0-19.1 mm air gap thickness	One-dimensional	In a very simple manner; completely transmitted radiation	Ignored the coupled effect of heat transfer modes
Sawcyn (2003)	Horizontal air gap; 0-19.1 mm air gap thickness	Quasi-multi-dimensional	Two-dimensional treatment of the radiation heat transfer; localized treatment of the convection heat transfer	Uncoupled heat transfer modes; improved the accuracy of prediction at lager air gap size
Talukdar *et al.* (2010)	Horizontal air gap; 0-19.1 mm air gap thickness	Multi-dimensional	Boussinesq approximation was used for solving the Navier-Stokes	Coupled conduction, convective and radiation heat transfer
Ghazy (2011)	Horizontal air gap; 0-6.35 mm air gap thickness	One-dimensional	Ignored the convective heat transfer; treated the air gap as a gray medium	Coupled conduction-radiation heat transfer
Udayraj *et al.* (2017a)	Horizontal and vertical air gap; 6.4-19.1 mm air gap thickness	Three-dimensional	Used an improved coupled CFD and radiation model	Coupled conduction, convective and radiation heat transfer
Dynamic air gap				
Ghazy (2012)	Horizontal air gap; 0-6.35 mm air gap thickness	One-dimensional	Used sinusoidal variation of the air gap as an approximation of body motion	Ignored the convective heat transfer
Udayraj *et al.* (2017a)	Horizontal and vertical air gap; 6.4-19.1 mm air gap thickness	Three-dimensional	Used sinusoidal variation of the air gap as an approximation of body motion	Used dynamic mesh technique

Table II. Typical models of heat transfer through air gap

the orientation of air gap and the dynamic change of air gap. According to the various heat transfer models, analysis follows these aspects: treatment of convective and radiant heat transfer, and coupling of heat transfer modes:

(1) Treatment of convective heat transfer.

It can be observed from the above studies that the characteristics of air gap affect the convective heat transfer. Previous studies show that beyond a certain range of air gap sizes, convection would occur, reducing the insulating effect. Furthermore, the orientation of air gap has a relation with the buoyancy, while convection heat transfer is induced by the buoyancy. In addition, human body motion can cause forced convection.

A finite model was developed by Torvi, (1997) to investigate the heat transfer through the air gap between fabric and sensor by conduction/convection and radiation, but the prediction for the larger air gap was considerately less accurate. For a single fabric, heat transfer through the air gap is mainly caused by conduction and radiation when the size of air gap between fabric and sensor was smaller than 6.35 mm. While the size of air gap is larger than 6.35 mm considered in Torvi's (1997) study, heat transfer through natural convection occurs (Torvi *et al.*, 1999). However, convection and radiation were treated in a very simple manner that air gap was considered as a slab with an effective thermal conductivity. Also, the assumption that the heat transfer is one-dimensional was thought as the main reason for Torvi's (1997) prediction difference with the measured results. Therefore, Sawcyn and Torvi (2009) improved the treatment of the heat transfer within air gap, using flow visualization studies to characterize the natural convection heat transfer in the air gap.

Based on the heat transfer model developed by Torvi (1997), Song (2003) established one-dimensional heat transfer model in the air gap between clothing and manikin, and Zhu *et al.* (2008) set up a one-dimensional radial heat transfer model in a cylindrical-coordinate system. They used Newton cooling formula to calculate the convective heat transfer within the air gap. As they neglected the coupling effect of the heat transfer modes, the prediction results made by their models and the experimental results had some differences. Ghazy (2014b) introduced new numerical model for both single-layer and multi-layer fabric-air gap-skin system which heat transfer through the air gap was considered different from the previous studies. However, with the assumption that the thickness of air gap was always smaller than 6.35 mm, convective heat transfer in the air gap in his research works was ignored which can be significant for the larger air gap. Later, convective heat transfer within the air gap was numerically considered in Talukdar *et al.*'s (2010) investigation. However, it was observed a significant difference between numerical results obtained from this study and the previous studies. The main reason for the difference lied in the Boussinesq approximation used to solve full Navier-Stokes equations. It should be noted that the Boussinesq approximation is only valid for small temperature difference instead of such large temperature difference in this problem (Torvi, 1997).

(2) Treatment of radiative heat transfer.

Research works had shown that radiative heat transfer dominated in the heat transfer mode through the air gap between fabric and sensor (Torvi, 1997; Torvi and Dale, 1999; Torvi *et al.*, 1999; Sawcyn and Torvi, 2009; Talukdar *et al.*, 2010; Ghazy and Bergstrom, 2010). The calculation (Torvi, 1997) had proved that the effect of absorbed and emitted radiation of carbon dioxide and water vapor on the net heat transfer through air gap was negligible. Therefore, the absorbed and emitted radiation was ignored by Torvi with regard to the air gap as a transparent body that completely transmitted radiation and the radiative heat transfer model in air gap using the view factor followed the Stefan-Boltzmann Law. The treatment with radiative heat transfer through air gap by Sawcyn (2003) was analogous to Torvi's (1997).

Furthermore, carbon dioxide and particle produced by chemical reaction of fabric and the increasing humidity of air gap beneath garment resulted from firemen's sweat both increase the absorbed and emitted radiation through air gap (Su, He and Li, 2016a, b; Su, Wang and Li, 2016). Therefore, the air gap was treated as gray body by Ghazy (2011), and the radiative transfer equation was established which considered the absorbed and emitted radiation through air gap. Considering the air gap as transparent medium, Talukdar *et al.* (2010) set up a radiative heat transfer model in the air gap using the finite volume method. With the assumption of air gap being transparent medium, discrete coordinate radiation (DOM) model was established by Udayraj *et al.* (2017a), which not only considered scattering, but could calculate the heat exchange between the gas and the particles.

(3) Coupled effect of heat transfer modes.

The heat transfer through the air gap was calculated by simply summing up contributions due to convection and radiation without considering the coupling of heat transfer modes in Torvi *et al.*'s (1999) studies. To improve the modeling of heat transfer through the air gap, heat transfer through air gap was treated in a different way by Ghazy (2014b), that coupled conduction-radiation heat transfer through the air gap was considered while the uncoupled method was taken in earlier studies. Momentum equation and energy equation considering coupled conduction, convection and radiation were presented in Talukdar *et al.*'s (2010) article.

However, the significant difference of the two studies was between the prediction made by these numerical models and the experimental result especially for the larger air gap. Heat transfer model coupled computational fluid dynamics (CFD) and radiation was improved upon Talukdar's model by Udayraj *et al.* (2017a).

4.1.2 Assumption of the equation dimension. Torvi (1997) developed a one-dimensional heat transfer model in the system of fabric, air gap and test sensor in ASTM D4108 bench-top test. This one-dimensional model means that the treatments of heat transfer between elements, which assumed the outside surface and inner surface of fabric to be entirely at uniform temperature at any time step. However, the results show that the prediction error attained to 12~15 percent when the size of air gap was in the range of 12.7-19.1 mm (Torvi *et al.*, 1999). A more sophisticated heat transfer model through air gap using finite volume method was introduced by Ghazy (2011), which was still one-dimensional.

Sawcyn (2003) later performed a standard bench-top test of 80 kW/m^2 flame exposure in ASTM D4108 and measured the bottom surface temperature of shim stock. Instead of a uniform temperature distribution, that temperature decreased from the center to the edge. Based on the obtained temperature, a quasi-multi-dimensional method was developed to treat the heat transfer through the air gap with a two-dimensional treatment of radiative heat transfer and a localized treatment of convective heat transfer (Sawcyn and Torvi, 2009). A two-dimensional heat transfer model through air gap using CFD modeling considering the coupled effect of convection, conduction and radiation was presented by Talukdar *et al.* (2010), which showed less accurate results at a higher air gap. Furthermore, the dynamic mesh technique in Fluent was used to investigate the effect of dynamic air gap, and a three-dimensional heat transfer model within air gap was introduced by Udayraj *et al.* (2017a). However, the numerical result was similarly low in accuracy with a larger air gap as shown in the findings of Sawcyn and Torvi (2009) due to the treatment of convection heat transfer using Boussinesq approximation which was not very accurate for a large temperature difference.

All the studies discussed above were focused on heat transfer through the horizontal orientation of air gap in the fabric level. However, some limitations exist in the bench-scale studies. For example, although various air gap thickness can be simulated using different spacers, only one air gap width can be used every time. And, in most tests the fabric lies above the heat source, while the air gap between clothing and body was always vertical in actual conditions. Recently, Tian *et al.* (2016) developed a three-dimensional finite volume model to simulate the heat transfer through simplified protective clothing by CFD. However, the condition of direct contact between clothing and skin was studied, and the uniform air gap size of 6.35 mm was studied as well, without considering the dynamic change of air gap width caused by fabric shrinkage during the flash flame exposure.

4.2 Modeling of dynamic air gap

Heat transfer through the air gap between protective clothing and human body exposed to high heat source was extensively studied. However, most previous research works assumed fixed or stationary air gaps. On the contrary, the dynamic changes in the air gap could be resulted from human body motion or fabric thermodynamics in actual situations. Therefore, the dynamics change function of air gap between fabric and skin was introduced into the heat transfer model through the air gap to simulate the variations of air gap. For one thing, the dynamic change in air gap width due to fabric thermal shrinkage was characterized as unidirectional linear variable thickness (Ghazy, 2014a). For another, the dynamic variation in air gap size was modeling which used a sinusoidal function (Xin *et al.*, 2014; Ghazy and Bergstrom, 2013).

A variation in the fabric shrinkage rate and the overall reduction in the fabric dimensions were introduced in Ghazy's (2014a) research to investigate the numerical effect of fabric thermal shrinkage on the protective performance. However, the variation indexes in air gap characteristics resulted from fabric thermal shrinkage were more than these. Ghazy (Ghazy and Bergstrom, 2013; Ghazy, 2012) also presented an approach which used sinusoidal variation function to model the dynamic air gap due to human body movement, but the convective heat transfer with the gap was not considered. A different method was performed by Udayraj *et al.* (2017a) as compared to that used by Ghazy. That is, dynamic mesh technique in ANSYS Fluent was used to explore the effect of sinusoidal variation in air gap due to body motion on the protection against flame exposure.

5. Influence of air gap on TPP

It can be observed from the previous research works (Wang and Li, 2015; Wang, Li and Li, 2015; Wang, Lu, Li and Pan, 2012; Wang, Zhang, Li and Li, 2012) that the air-spaced configuration could significantly decrease the heat transfer to the testing sensor behind the fabric assemblies under the combined convective and radiant heat exposure. Therefore, the air gap improved the TPP especially when the air gap width is less than 7~8 mm. This is mainly because of the lower thermal conductivity of the air. The air gap added between the testing fabrics and sensor hinders the conductive and radiant heat transfer with the assumption that no convective heat transfer occurs within the air gap.

Previous research works had proved the positive effect of air gap without considering the discharge of stored energy in fabrics assemblies after exposure. Even if the dual effect of protective clothing was considered, the added air gap between the specimen and the sensor improved the thermal protection performance under 84 kW/m^2 heat flux (He and Li, 2016). On the one hand, the total stored thermal energy for fabric system during exposure predicted by Su, He and Li (2016a, b) and Su, Wang and Li (2016) increased when the air gap size increased in the range of 0-6.4 mm. On the other hand, an experimental study (He *et al.*, 2017) had demonstrated that the 6.4 mm air gap added between fabrics and sensor could also reduce heat transfer by decreasing the heat discharge from the fabric after 8.5 kW/m^2 radiant exposure.

5.1 Air gap thickness

The essential and complicated role of air gap in determining the performance of protective clothing during thermal exposure attracts the researchers' interest. The size and distribution of the air gap present in the clothing system are important roles governing energy transfer by convection, conduction and radiation. In standard thermal protective clothing (TPP) test, there are still controversies about the presence or absence of air gap between fabric specimen and test sensor, as well as whether the air gap size of 6.35 mm can simulate the effect of different sizes on TPP in actual dressed condition (Torvi, 1997).

Torvi *et al.* (1999) found that the TPP of the flame-retardant fabric improved with the increasing size of the air gap when subjected to the contact flame of 80 kW/m^2. While the fabric assemblies were exposed to an 84 kW/m^2 radiant heat, the thicker air gap could provide higher thermal protection, but the increment of protection is less apparent below a certain air gap width (Li, Lu and Li, 2012). However, if the air gap further increased, the TPP of fabric would increase markedly again. When the fabric system was exposed to the medium radiant heat flux of 21 kW/m^2, the heat flux received by the simulated skin firstly decreased and then increased as the thickness of the air gap increased (Zhu *et al.*, 2008). The increasing of the thickness of air gap could prolong the time to second-degree burn during the exposure of low-level radiant heat and after the heat exposure (Fu *et al.*, 2014a, b). Furthermore, a study showed that the air gap between the clothing and the skin not only provided better thermal protection for dry radiant heat exposure, also slowed down the steam transfer rate to provide heat protection (Su *et al.*, 2017). However, He *et al.* (2012) experimentally found the temperature on the simulated skin increased with the air gap until the thickness reached 7 mm when the fabric was exposed to radiative heat flux of 5 kW/m^2 due to the convective heat transfer in the air gap cannot be ignored when the air gap thickness was larger than 7 mm.

The studies discussed above considered the effect of air gap based on the small specimens of fabric in bench-scale test where only one air gap thickness can be used every time that is, bench-top tests do not account for the non-uniform thickness of air gap distributed over the different body locations. In addition, the style, size and fit of garments define the thickness of air gap under clothing (Crown *et al.*, 1998; Song, 2007; Mah and Song, 2010a, b). Full-scale manikin tests using garments have been conducted to examine the effect of air gap on thermal performance. The flame-manikin system was employed by Song to evaluate the protective performance of different sized clothing exposed to the flash fire of 83 kW/m^2, indicating that the optimum width of air gap was about 7-8 mm for a single-layer garment (Song, 2007). His other study of female mannequin test showed that no or smaller air gaps were more susceptible to burns than area with larger air gaps, due to the absence or reduction of insulating space (Mah and Song, 2010b). On the other hand, Tian (2016) developed a uniform clothed CFD model depending upon Donghua flame-manikin system to analyze the heat transfer mechanism for the different sizes of air gap, showing that oversize or undersize air gap thickness might decrease the protective performance of garment system. And this result consisted with the conclusion of the bench-scale tests. Moreover, the optimum air gape size exists in the range of 3-12 mm with the uniform thickness of air gap distribution over the manikin body.

5.2 Air gap location

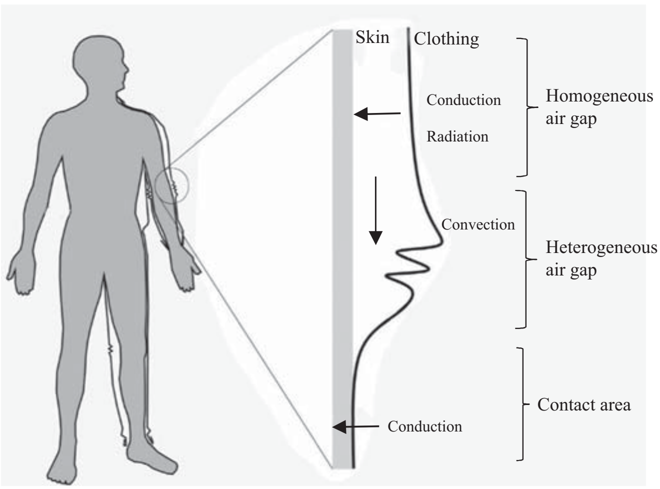
The air gap is not only distributed between clothing and body, but also entraps within the clothing layers. The air gap within multiple fabric layers provided extra protection compared to a single-layer (Brewster and Barker, 1983; Baitinger and Konopasek, 1986). Moreover, Jiang *et al.* (Jiang *et al.*, 2010) experimentally and numerically compared three fabric layers in close contact with fabric layers with air gaps in the ISO 6942 experiment, showing the insulating effect of air. Many researchers focus on the effects of air gap between fabric sample and test sensor used in bench-top tester, while few studies focused on the difference with varying air gap location. To investigate the impact of location of horizontal air gap on flame protection exposed to open flame contact of 80 kW/m^2, Ghazy and Bergstrom (2012) numerically simulated the heat transfer in multiple air gaps, showing that the influence of the air gaps entrapped in the clothing system on the overall performance increased from the exterior to the interior. Fu *et al.* (2014a) experimentally proved that the protective performance of air gap between outer shell and moisture barrier against low-level heat exposure was higher than the same size of air gap between moisture barrier and thermal liner. This conclusion was in accord with the result (Ghazy and Bergstrom, 2012) that increasing the width of moisture barrier-thermal liner air gap had a larger effect on reducing the skin temperature than of increasing the outer shell-moisture barrier air gap width.

Coupled effects of air gap and moisture on the performance of clothing system were studied to simulate real wearing conditions of thermal protective garments. Wang, Lu, Li and Pan (2012) and Wang, Zhang, Li and Li (2012) used the TPP tester to demonstrate that the air gap position greatly influenced the heat transfer when exposed to flash fire, and the TPP value increased as the air gap was further from heat source for both dry and wet multi-layer fabric combinations. He *et al.*'s (2016) study was based on 21 kW/m^2 of radiant heat exposure simulated by TPP tester, and for the dry configurations, the second-degree burn time increased as the air gap moved further from the heat source, which was contrary to the burn time response under wet conditions. However, the result for the wet fabric system that the second-degree burn time decreased as the air gap was closer to the heat source was inconsistent with Wang, Lu, Li and Pan (2012) and Wang, Zhang, Li and Li (2012). Huang and HE (2015) employed a heat and moisture transfer model to investigate the impact of vertical air gap position on the heat insulation performance of the firefighters' clothing, proving that the thermal insulation performance of the fabric-air gap system when the air gap existed between the outer and moisture layer was better compared to locating the air gap between the comfort layer and the human skin at the same thickness. And the time before human skin subjecting to first and second-degree burns was also prolonged when the air gap is located between the outer layer and the moisture layer which was contrary to Ghazy and Bergstrom's (2012) findings.

It can be observed from the above studies that the location of the air gap has an effect on the TPP of fabric combinations. This is also related to the heat conditions, air gap orientation, etc. Present discussions about how the air gap position affects the TPP is limited to the small specimens of fabric, due to the technical difficulties of 3D body scanner which cannot get the distribution of air gap within clothing layers. Recently, a scholar (McQuerry, 2016) presented a novel method using 3D body scanners to measure the air gap of the outer shell, moisture barrier and thermal liner layers by taking down the other two clothing layers when measure a single-layer clothing. However, this method has a relatively large drawback in the manual operation of removing the clothing layer, and has difficulties in doing so to the deformed clothing after the heat exposure.

5.3 Air gap heterogeneity

Currently, most of experimental and numerical studies either assumed that the air gap available between fabric and sensor was uniform or they assumed perfect contact between the body and the garment. They overlooked partial thickness and contact area of air gaps. In actual conditions, the air gap present between clothing and body is not uniform (Figure 5) because of the complexity of human bodies and the characteristics of the fabrics (Psikuta *et al.*, 2017). As shown in Figure 5, the heterogeneity of air gap can be summarized as the non-uniform thickness of air gap and the existence of direct contact area depending upon the body locations.



Source: Psikuta *et al.* (2017)

Figure 5.
Distribution of air gap between clothing and body

Three-dimensional scanning (Song *et al.*, 2004; Kim *et al.*, 2002; Mah and Song, 2010a; Mah and Song, 2010b) provides an efficient means to visualize and quantify the air gap between clothing and body. A 3D human body scanner was used to determine the air gap distribution of dressed manikin, showing that the air gap was not evenly distributed with the thinner air gap in shoulder, chest, upper back and hip, and the thicker air gap in waist, thigh and crotch (Wang, Lu, Li and Pan, 2012; Wang, Zhang, Li and Li, 2012). A few studies (Mayor *et al.*, 2014; Mert *et al.*, 2015) are available where the effect of heterogeneous or wavy air gap was analyzed, but these studies were not at all related to the thermal protective clothing. Mayor *et al.* (2014) used numerical simulation to explore the transport phenomena in clothing wavy horizontal microclimates, finding that it was largely depended on the amplitude of wavy microclimates. Then, to investigate the effect of a heterogeneous vertical air gap on dry loss, Mert *et al.* (2015) used a heated cylinder (torso) setting up different configuration of folds (size and frequency) outside the cylinder. Inspired by this, Udayraj *et al.* (2017b) numerically analyzed the effect of heterogeneous air gap on heat transfer through air gap and skin burn injuries, demonstrating that as compared to the homogeneous air gap cases, heterogeneous air gap resulted in more heat transfer across horizontal and vertical air gaps. Here, the regular folds in fabric level were used to mimic the real clothing shape, while compared with the real air gap formed by the irregular shape of clothing there is still a huge gap.

The other characteristic of the heterogeneity of air gap is contact area. Psikuta *et al.* (2012) defined the concept of contact area as the air gap in which the thickness value was 0, i.e. clothing and body fit closely together. The distribution of the clothed Donghua flame-manikin after the flash fire exposure was determined using portable 3D body scanning technology, and the results showed the clothing at breast, upper back, front of thigh and calf was closely contact with the manikin body (Wang *et al.*, 2016). In thermal protection tests, the lowest time to burn injury almost always occur in contact tests compared to air-spaced configuration, because the energy transferred by conduction was maximized when fabric touches skin (Krasny, 1986; Crown *et al.*, 2002). Mah and Song (2010b) using instrumented female mannequin showed that 51 sensors (71 percent) in a total of 80 sensors reaching the second-degree burn criteria had no air gap. Moreover, a parametric study shows that the contact heat transfer can weaken the importance of air gap (Su, He and Li, 2016a, b; Su, Wang and Li, 2016). Therefore, it is essential to qualify the direct contact area and explore further the heat transfer mechanism in clothing microclimates.

5.4 Air gap orientation

In experimental studies of the fabric level, the orientation of the air gap between the fabric and sensor is set to simulate the air gap available between clothing and human body. Figure 6 has shown the configurations of the system of heat source-fabric-sensor in terms of the orientation.

The orientation of the air gap has a direct effect on convection heat transfer through the air gap. The convective heat exchange is calculated using Newton cooling formula shown as

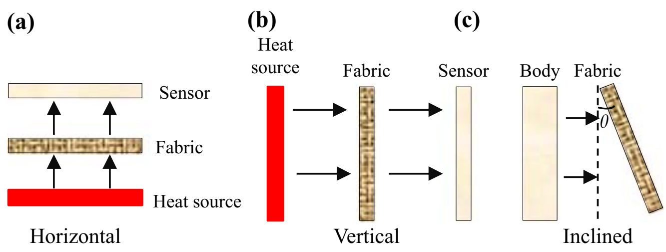


Figure 6.
Air gap orientations setting

Equations (1) and (2). Besides, convection heat transfer is caused by buoyancy, while the temperature difference in fluid leads to this buoyancy, which is related with the orientation of the air gap, as shown in Equation (3) (Hollands *et al.*, 1975; Ostrach, 1988). A numerical study conducted by Udayraj *et al.* (2017a) had shown that a significant difference in convective heat flux between the results of horizontal and vertical air gap:

$$q_{\mathrm{conv}} = h\,(T_{\mathrm{fab}} - T_{\mathrm{skin}}) \tag{1}$$

$$h = \mathrm{Nu}\frac{k}{L} \tag{2}$$

$$Nu = \begin{cases} 1+1.44\left[1-\frac{1{,}708}{Ra}\right]+\left[\left(\frac{Ra}{5{,}830}\right)^{\frac{1}{3}}-1\right]^{0} & \text{(horizontal air gap)} \\ \begin{cases} 1.0 \quad Ra \leqslant 1{,}713 & \text{(vertical air gap)} \\ 0.112Ra^{0.294} \quad Ra \geqslant 1{,}713 & \text{(vertical air gap)} \end{cases} \end{cases} \tag{3}$$

where h is the convective heat transfer coefficient of air gap; T_{fab} is the fabric inner temperature; T_{skin} is the epidermis temperature; Nu is Nusselt number; L is the thickness of the air gap; $[\;]^0$ represents that if the value in square brackets is negative, this item takes 0; Ra is the Rayleigh number.

Most of the previous research works on the heat transfer within the air gap considered the air gap to be horizontal which was different from the truth that this air gap is mostly always vertical. Only until recently, a research (Udayraj *et al.*, 2017a) numerically analyzed the vertical air gap and consequent characteristics of heat transfer process in case of the vertical orientation as compared to the horizontal orientation. It had been proved that the fabric-air gap system with vertical air gap orientation offered more thermal protection against skin burn injuries than the horizontal case, and the difference between the two orientations increased with the increase in the extent of air gap available between the shim stock and the sensor. Depending upon the body postures and body locations, the air gap also can be in inclined orientation. Moreover, a study (Mayor *et al.*, 2015) on the transport phenomena in the titled clothing microclimates was conducted numerically, proving the importance of microclimates inclination in determining the transport of clothing.

5.5 Dynamical air gap

In actual fire ground, the firemen inevitably undergo body movement during fire-fighting or rescuing operations, which can cause the air gap to dynamically change (Ghazy, 2012). In addition, dynamic air gap can be induced by the thermal shrinkage of fabric (Ghazy and Bergstrom, 2011). It can be found that few studies took into the consideration the changes of air gap due to the thermal shrinkage during the heat exposure when analyzing the heat transfer through the air gap.

5.5.1 Effect of body motion on TPP. Body motion of the wearer in a fire could result from fire-fighting operation of firemen or result from the movement of escaping from the fire ground. A case study of Li *et al.* (2011) presented the leg movement of running (Figure 7). It can be observed that the air gap between fabric and body dynamically changes due to the human body motion.

Some researchers (Xin *et al.*, 2014; Ghazy and Bergstrom, 2013; Ghazy, 2012; Udayraj *et al.*, 2017a) used the sinusoidal variation of air gap as an approximation of the dynamic

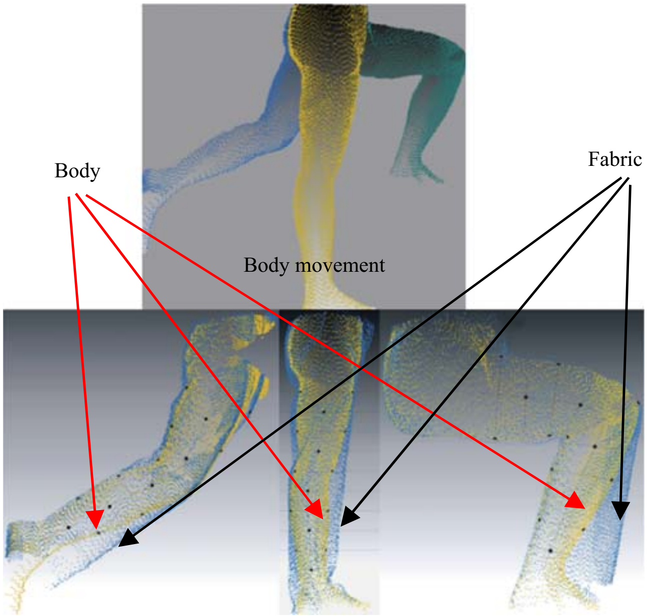


Figure 7.
Scanning images of simulating human running movement

Source: Li *et al.* (2011)

changes of air gap due to body motion. A TPP tester was modified to explore the effect of dynamic air gap on TPP of fabric by Xin *et al.* (2014). Three different frequencies of the sinusoidal air gap size variations were studied experimentally, showing that the effect of frequency of air gap size change on the sensor temperature rise was not significant. A numerical study (Ghazy and Bergstrom, 2013) was conducted by Ghazy to analyze the effect of frequency and amplitude of the periodic movement of air gap on the clothing performance. The results showed that the movement frequency had a positive effect on the TPP value of fabric, while the amplitude had a negative effect on the TPP value of fabric. However, the process of the convective heat transfer was not considered in Ghazy's research works (Ghazy and Bergstrom, 2013; Ghazy, 2012), which was not against the facts that forced convection through air gap could be produced by the body movement found by Xin *et al.*'s (2014) experimental study. Udayraj *et al.* (2017a) investigated the effect of dynamic air gap induced by the body motion on the heat transfer through the air gap during the contact flame exposure by the dynamic mesh technique. Two different frequencies in air gap sinusoidal variation were investigated numerically for both horizontal and vertical orientations of air gap. It could be observed from the results that the effect of dynamic air gap on the sensor temperature rise was less significant which in agreement with the results of (Xin *et al.*, 2014), while the effect on the convection and radiation heat transfer was significant. Moreover, the fluctuations of convective heat and radiative heat increased with the increasing of the movement frequencies.

5.5.2 Effect of fabric shrinkage on TPP. Thermal shrinkage of the protective fabric could occur during the high heat exposure (Ghazy, 2014a), and the fabric shrinkage would result in the changes of three-dimensional morphology of protective clothing (Figure 8). Moreover, the clothing geometry affected the size and distribution of air gap entrapped beneath the clothing, and the dynamic changes of air gap would lead to a corresponding variation in the heat transfer through the air gap, thus affecting the TPP of clothing.

Figure 8.
3D morphology of protective clothing

On the one hand, the fabric shrinkage could reduce the thickness of the insulating air gap, resulting in the increasing total energy transferred to human skin (Li, Li, Lu and Wang, 2012). Ghazy (2014a) presented a novel approach that the air gap variations caused by fabric thermal shrinkage was numerically simulated by a linear function. It demonstrated that the effect of reduction in air gap width due to fabric shrinkage was more influential on the protective performance of clothing compared to the reduction rate. On the other hand, the thermal shrinkage could lead to two cases of no air gap. A special case occurred as the human skin directly exposed to the high heat (Figure 8), which was usually observed from the slack bottoms or the cuffs due to the dramatic shrinkage in clothing dimension. Another case was in the form of direct contact skin, and conduction heat transfer due to this significantly increased, causing more severe skin burn injuries (Abbott and Schulman, 1976).

6. Future research suggestions

In bench-top tests, the distribution characteristics of air gap beneath the fabric were simulated based on the corresponding standard requirement or self-designed air gap size, orientation and location. Then qualitative analysis of effect of air gap characteristics on the TPP was conducted by a bench-scale tester. In full-scale manikin tests, the characteristics of air gap distributed over the manikin body were gained by employing the three-dimensional body scanning technology, and based on that scanning data, the influence of stationary air gap on the protective performance against skin burns was investigated. In the numerical studies, researchers focused on the one-dimensional heat transfer through the air gap in fabric level exposed to a high heat source with the idealized modeling conditions. In addition, tentative exploration has been conducted in dynamic air gap due to fabric thermal shrinkage and human body motion. Therefore, the research in effects of air gap characteristics on the clothing TPP could be conducted from the following three aspects in future.

6.1 Detailed characterization of air gap distribution

Studies on the location of air gap were focused on the air gap between clothing and body due to difficulty in qualifying the air gap entrapped in the clothing layers as the limitation of three-dimensional body scanner. For the orientation of air gap, most of experimental studies and standard TPP tester consider horizontal orientation of air gap, while the air gap between clothing and human body is almost always vertical. Moreover, tilted air gap also exists between clothing and body, with a study showing that the flow patterns inside clothing microclimates strongly depend on the inclination (relative to gravity direction) of air gap, which stressing the need for analyzing other orientations of air gap within clothing. Furthermore, one of the urgent needs is to characterize the heterogeneity of air gap.

6.2 *Thorough explorations for the heat transfer mechanism*

The investigation on the coupled effect of different heat transfer modes within the air gap is proposed on the basis of detailed characterization of air gap distribution. For example, force convection produced by body movement should be considered in the modeling of heat transfer through the air gap. It is essential to begin research works on a sub-regional strategy for the thermal protective clothing, especially for the higher clothing thermal shrinkage areas. By qualifying the contact area where the clothing directly touches human skin, the energy attributed by conduction is expected to be quantitatively differentiated. In addition, He *et al.* did not consider storage-release effect of the air gap under the fabric assemblies, as that the narrow air gap is weakly capable of storing heat. However, it is deserved to study the storage-release effect of the air for a large air gap case.

6.3 *Numerical simulation of there-dimensional heat transfer in clothing level*

A researcher (Tian, 2016) developed a three-dimensional transient heat transfer model of uniform clothed manikin located in the combustion chamber depending upon the Donghua flame-manikin system by CFD. It was assumed that the air gap between single clothing layer and manikin body was always uniform and fixed during the flash fire exposure, although the flame-manikin test showed that clothing shrinkage of the clothing samples lead to the dynamic changes in air gap thickness and average volume. Another CFD model (Wang, Li and Tian, 2015) was built to simulate 3D heat transfer within single-layer protective clothing made of Nomex IIIA, eliminating the effect of air gap with close-fitting garment design. However, this clothing material has the feature of easy shrinkage and deformation after heat exposure (Morse *et al.*, 1973), and eventually results in the dynamic variation of air gap under the clothing. Therefore, the heat transfer model considering dynamic change of air gap induced by fabric thermal shrinkage should be developed to improve the accuracy of prediction in the TPP of clothing. By the three-dimensional body scanning and reverse engineering, the air gap distribution beneath the clothing can be acquired before and after heat exposure, while the dynamic variation of air gap with time during the heat exposure cannot be detected. The indirect index for the characterizing the dynamic air gap under a garment is worthy of study in the future research works.

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