THE EFFECT OF AIR GAP ENTRAPPED IN FIREFIGHTER PROTECTIVE GARMENT ON THERMAL BEHAVIOUR

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A thesis submitted to the

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Dedication

I'm dedicating this thesis to my parents in particular, they always encouraged me to be a good academician - *Praise be to Allah* - I greatly appreciate their loving and support, *and, in general, to my awesome family, I am very grateful for their support; To my friends and classmates, thank you.*

Acknowledgment

At first, Praise be to Allah for giving me the opportunity and potential to pursue this Master study and the wisdom and strength to complete this successfully. The journey of this study made me realize how fortunate I am as a person, I started my master's study under the supervision of Pr. Paulo Piloto and Mr. Salim Dahamni, and with the help of Pr. Abdallah Benarous, I couldn't ask for more - Praise be to Allah – they've been a great support for me in this journey.

Resumo

O principal objetivo deste trabalho é investigar o desempenho de proteção térmica (TPP) de vestuário de bombeiros quando exposto durante 10s/20s a várias solicitações térmicas, analisando o efeito da camada de ar, o efeito da espessura do tecido e a intensidade de calor radiante (utilizando tecidos Kevlar/PBI e NOMEX) na previsão de queimadura da pele. As simulações numéricas foram realizadas utilizando o programa ANSYS, de acordo com as propriedades térmicas dependentes da temperatura dos materiais.

Foi desenvolvido um modelo de cálculo numérico por elementos finitos, considerando a taxa de perfusão sanguínea. O modelo é validado em relação a testes experimentais e em relação a resultados numéricos de outros autores.

Foi desenvolvido um estudo paramétrico, com base num conjunto de 500 simulações. Os resultados obtidos são tratados para avaliar e estudar o efeito dos fatores acima mencionados sobre o desempenho TPP do vestuário de bombeiros e previsões de queimaduras da pele. Finalmente, com base nos resultados numéricos determinados para exposições a elevados valores de radiação e para tempos de exposição elevados (20 s), é apresentada uma nova proposta para determinar o tempo para atingir queimaduras de primeiro, segundo e terceiro grau na pele.

Palavras Chave: Segurança contra incêndios, Camada de ar, Vestuário de proteção dos bombeiros, Isolamento térmico, Lesões cutâneas.

Abstract

The main objective of this work is to investigate the thermal protective performance (TPP) of firefighter's garments under 10s/20s of various thermal exposures, shedding light on the effect of the air gap, the effect of fabric thickness and the radiant heat intensity (using Kevlar/PBI and Nomex fabrics) on skin burn predictions. The numerical simulations were performed using the ANSYS software in accordance with the temperature-dependent thermal properties of the materials.

A numerical calculation model by finite elements is developed considering the blood perfusion rate. The model is validated against experimental tests and against numerical results from other authors.

A parametric analysis was developed upon a set of 500 simulations. The results obtained are treated to evaluate and study the effect of the above-mentioned factors on TPP of firefighter's garments and skin burn predictions. Finally, based on the numerical results determined for high flash fire and for high exposure time (20 s), a new proposal is presented to determine the time to reach the first, second and third-degree skin burn.

Keywords: Fire safety, Air gap, Firefighters protective clothing, Thermal insulation, Skin injuries.

الملخص

الهدف الرئيسي من هذا العمل هو التحقق من أداء الحماية الحرارية لملابس رجال الإطفاء تحت 20/10 ثانية من التعرضات الحرارية المختلفة ، وإلقاء الضوء على تأثير فجوة الهواء ، وتأثير سماكة النسيج وكثافة الحرارة المشعة (باستخدام KEVLAR/PBI و Nomex) على تنبؤات حروق الجلد. تم إجراء عمليات المحاكاة الرقمية باستخدام برنامج "ANSYS" وفقًا لخصائص المواد الحرارية المعتمدة على درجة الحرارة.

تم تطوير نموذج حساب رقمي بواسطة العناصر محدودة مع الأخذ بعين الاعتبار معدل نضح الدم. في وقت لاحق ، تم التحقق من صحة النموذج بالمقارنة مع الاختبارات التجريبية والنتائج العددية من المؤلفين الآخرين.

تم تطوير التحليل المعياري على مجموعة من 500 محاكاة ، وتم معالجة النتائج التي تم الحصول عليها لتقييم ودراسة تأثير العوامل المذكورة أعلاه على أداء الحماية الحرارية لملابس رجال الإطفاء وتنبؤات حرق الجلد ، وأخيراً بناءً على النتائج العددية المحددة لنيران وميض عالية ولوقت التعرض العالي (20 ثانية) ، يتم تقديم اقتراح جديد لتحديد الوقت اللازم للوصول إلى حروق الجلد من الدرجة الأولى والثانية والثالثة.

الكلمات المفتاحية: الحماية من الحرائق ، فجوة الهواء ، الملابس الواقية لرجال الحماية المدنية، رجال الإطفاء ، العزل الحراري ، حرائق الجلد.

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Nomenclature

A	surface area	[m^2]
C	heat capacity	[J/kg K]
C_p	specific heat at constant pressure	[J/kg K]
h	convective heat transfer coefficient	[W/m^2 K]
K	thermal conductivity	[W/m K]
L	thickness	[m]
P	pre-exponential factor	[1/s]
T	temperature	[K]
t	time	[s]
y	linear vertical coordinate	[m]
ΔE	activation energy of skin	[J/kmol]
ρ	density	[kg/m^3]
ω	blood perfusion rate	[$m^3/s/m^3$]
ϕ	Heat flux	[kW/m^2]
ε	emissivity	
Ω	quantitative measure of skin damage	

Subscripts

air	Air
amb	Ambient conditions
b	Human blood
cnv	Convective heat transfer
cnd	Conductive heat transfer
cr	Human body core
ep	epidermis
ds	dermis
sc	Subcutaneous

exp	exposure
fbr	fabric
rad	Radiation heat transfer
x,y,z	Coordinate directions

Chapter 1: INTRODUCTION

1.1 Background

Fires are a major cause of fatalities and injuries. According to the international association of fire and rescue services (CTIF)'s last report, it is estimated that in 2018 over 51,360 persons injured in fire incidents and over 30,860 persons died in fires in 56 countries of the word. Human cost in terms of firefighter injuries and deaths were also very high. The CTIF fire statistics confirmed injuries to 59,909 firefighters and a death toll of 91 firefighters in various fire incidents across the world (only in the countries that provided fire statistics to the CTIF). As protective clothing is the only barrier between firefighters and the fire hazards, the majority of burn injuries are caused by the inadequate performance of their protective clothing (Kahn, et al., 2012).

During firefighting, firefighters are subjected to multiple fire conditions. They can be burned by radiant energy that is produced by a fire and flame contact exposure. The most common exposure is to low radiant heat flux over long periods of time.

The thermal performance of fire fighters' protective clothing has been the most significant point and discussion for decades. Most of these discussions are based on fire services field experience. Most of them still needs to be done in terms of scientific analysis for predicting the thermal protective performance of clothing throughout the range of fire environments faced by a firefighter. Fundamentally speaking, this problem can be viewed as the study of heat transfer through textile fabrics.

Prediction of protective garment performance in preventing or minimizing tissue burns essentially needs the ability to understand and model heat transfer from the incident radiant and/or convective heat sources to and through the protective clothing fabric, through an interfacial air gap, and, finally, through the skin. This project considers the effect of the air gap entrapped in the firefighter protective garment.

To measure the effect of the air gap entrapped in the garment, few experiments were conducted, but it was enough to provide just the required input to improve the thermal protective performance (TPP) of the garment, and gave an idea on the garment thermal resistance limits to not affect the wearer comfort.

To understand the influence of fire incidents on the human skin, we need to study the Bio-Heat transfer phenomena. Because the biochemical are not temperature independent, heat transfer plays an important role in living organisms. Also, because the transport of blood through tissue results in a consequent thermal energy transfer, bioheat transfer methods are applicable for diagnostic applications involving mass and heat transfer, or either one of them (Valvano, 2006).

The study of bioheat transfer involves phenomena that are only found in systems that are alive. For example, blood perfusion is considered a three-dimensional process as fluid crosses in a volumetric manner through tissues and organs via a complex media of forking vessels. In general, heat transfer is affected by local blood flow rates, vessel geometry, and thermal capacity of the blood.

A very limited amount of experiments was conducted to study and analyse the effect of thermal exposure on the human skin, as well as measuring the time to first-degree burn, leaving the research community in this field with a very limited data to deal with. To fill the gap, many models were developed to calculate the burn for different levels of thermal exposure, which will be discussed in chapter two of this thesis.

1.2 Definitions

Conduction or conductive heat transfer: Conduction heat transfer is the transfer of heat by means of molecular excitement within a material without bulk motion of the matter. Conduction heat transfer in gases and liquids is due to the collisions and diffusion of the molecules during their random motion. On the other hand, heat transfer in solids is due to the combination of lattice vibrations of the molecules and the energy transport by free electrons (Ghassemi & Shahidian, 2017).

Convection heat transfer: Convection occurs when there is conduction of heat into the molecules of a fluid and the bulk motion of that fluid that carries those molecules away from the heat source. Typically, it is used to describe the heat exchange at a surface due to the movement of air across that surface (Matthew , 2010).

Radiation or radiative heat transfer is the transfer of heat from one place to another through infrared radiation (a type of electromagnetic radiation). This heat transfer can also occur through empty spaces (Siegel & Howell, 2002).

Emissivity: is defined as the ratio of the thermal energy irradiated from a material's surface to that irradiated from a blackbody (a perfect emitter) at the same temperature and wavelength under the same viewing conditions (Hsu, 1963) .

Heat flux: is the thermal intensity indicated by the amount of energy transmitted per unit area per unit time (Lienhard & Lienhard, 2011).

Heat transfer: is the movement of thermal energy from one object to another object of different temperature (Lienhard & Lienhard, 2011)

Specific heat: is the heat required to raise the temperature of the unit mass of a given substance by a given amount (usually one degree) (Bergman, et al., 2011)

Thermal conductivity: is the rate at which heat passes through a specified material, expressed as the amount of heat that flows per unit time through a unit area with a temperature gradient of one degree per unit distance (Bergman, et al., 2011; Hsu, 1963).

Thermal insulation of a fabric: is the reduction of heat transfer (the transfer of thermal energy between objects of differing temperature) between objects in thermal contact or in range of radiative influence (Abdel-Rehim, Saad, Ei-shakankery, & Hanafy, 2006; Song, 2009).

Thermal protective performance of a fabric: thermal protective performance of a fabric is defined as the minimum exposure energy required to cause the accumulated energy received by the copper sensor to equal the energy that can cause a second-degree burn in human tissue (ASTM International, 2008).

Thermal resistance of a fabric is the resistance of the fabric to the heat transfer through conduction, convection, and/or radiation (ASTM International, 2014a).

Thickness of a fabric is a precise measurement of the distance between two plane parallel plates separated by the fabric when a known pressure is applied and maintained on the plates (ASTM International, 2013a).

Thermal absorptivity: is the property of a material that determines the fraction of incident thermal radiation absorbed by the material (Bergman, et al., 2011; Hsu, 1963).

Porosity of a fabric: is a measure of the void (i.e., empty) spaces in a fabric, and is a fraction of the volume of voids over the total volume (A.S.T.M International, 2013a). The porosity values lie between 0 and 1 or it can be expressed as a percentage between 0 and 100%.

Woven fabric: is a structure produced when at least two sets of yarns are interlaced, usually at right angles to each other, according to a predetermined pattern of interlacing, and such that at least one set is parallel to the axis along the lengthwise direction of the fabric (ASTM International, 2013a).

1.3 Aim of the thesis

Safety of industrial workers and firefighters operating under hazardous conditions is a major concern now-a-day. These people encounter various level of heat and flame exposure while performing duty. Exposure to medium or high levels of such heat exposure decreases the performance of the worker.

This thesis aims to investigate the thermal protective performance (TPP) of a one-layer assembly firefighters protective clothing, affected by the exposure time, the fabric thickness and the air gap entrapped in between the protective clothing and the human skin, under the exposure of low, medium and high thermal radiation.

1.4 Thesis outline

This thesis is divided into five chapters: the first chapter introduces the research and provides a background for the study; the research problem is presented, and the objectives and contributions of the study are explained. The second chapter thoroughly reviews the literature on the thermal protective performance of fabrics under various thermal exposures as well as the human skin behaviour under thermal exposure. Through this review, various fabric properties that affect the thermal protective performance of fabrics are presented. The important knowledge gaps in the existing research are identified to provide the rationale for the objectives of this study. Also, in this chapter a literature review is presented on textile tests standards and the flame-retardant materials. The third chapter presents the main problem for this thesis which is the mathematical model of the bio heat transfer system, which consists of the protective clothing, the air gap, and the skin, and then finishing with the numerical validation with experimental test. In chapter four, using the model built in chapter three, in which the effect of radiant heat flux, the effect of the radiant heat flux exposure time, the effect of fabrics thermal properties, and the effect of the air gap size are discussed as well as the results discussions, later on in this chapter, A proposal for Skin burn prediction is presented. Finally, chapter five will present the conclusions and provide ideas for future research work.

Chapter 2: State of the Art

2.1 Previous research on thermal protective performance of fabrics

Many researchers have studied the thermal protective performance of fabrics used in firefighters' clothing under one or multiple thermal exposures (Benisek & Phillips, 1981; Lu, et al., 2014; Rossi, et al., 2004; Shalev & Barker, 1984). In these studies, the thermal protective performance of the fabrics was evaluated using the test methods developed by many national and international organizations such as ASTM, International Organization for Standardization (ISO), and NFPA (International A.S.T.M, 2008a; International A.S.T.M, 2008b; International A.S.T.M, 2008c; International A.S.T.M, 2013b; I.S.O., 1995; N.F.P.A., 2013). These studies have also characterized the fabrics in order to recognize and explain fabric properties affecting the thermal protective performance.

In the late 1970s and early 1980s, (Benisek & Phillips, 1979) analysed single- and double-layered fabrics in the high intensity flame exposures. They found that the thickness and weight of fabrics affected the thermal protective performance, and the double layered fabrics protection was much higher than that of single-layered fabrics. (Barker & Lee, 1987), and (Barker, et al., 2006) demonstrated that the thermal protective performance of single layered fabrics was affected by changes in the intensity of the flame exposure and also by the thickness and weight of the fabrics. (Barker & Lee, 1987) further explained that the fabric's density (mass per unit volume) does have a significant impact on thermal protective performance. Here, if the density of a fabric gradually increases, the thermal protective performance proportionately decreases. However, over the density of ~60 kg/m3, the thermal protective performance drops very rapidly. This is because, beyond this density, the embedded air trapped inside the fabric structure starts conducting the thermal energy toward the wearer's skin. This situation rapidly lowers the thermal protective performance of the fabric. Furthermore, (Morris, 1953) explained that when two fabrics having equal thickness, the one with lower density shows greater thermal protective performance. In this context, it is necessary to remember that the structural properties of two fabrics with the same density can be quite different. One fabric might be loosely woven from tightly twisted, hard yarns and the other might be closely woven from loosely twisted, soft yarns. This variation in structural properties may affect the thermal protective performance of the fabrics. Contextually, (Torvi & Dale, 1998), also (Torvi, et al., 1999) found that a fabric with high thermal conductivity and low specific heat could quickly transfer thermal energy through it and lower the thermal protective performance. They also noted that such fabric could decompose in a flame exposure. Here, the thermal decomposition reactions of the fabric are generally endothermic because little oxygen is available for exothermic oxidation reactions to happen (Torvi, 1997). This endothermic decomposition reaction could generate considerable thermal energy depending upon the intensity and duration of the flame exposure. This thermal energy generated by decomposition could also lower the thermal protective performance of the fabric.

In a bench-top configuration that simulated a combined exposure of flame and radiant heat, (Shalev & Barker, 1984) observed that the thermal energy transfer rate was lower for thick fabrics than for thin fabrics, and that the air permeability of the fabrics did not significantly affect the transfer of thermal energy. They concluded that air permeability has little or no impact on thermal protective performance of fabrics. (Perkins, 1979) concluded that fabric weight and thickness are the main properties to consider when analysing fabric performance in low intensity (~ < 20 kW/m^2), radiant heat exposures. Through statistical analysis, he confirmed that fabric weight and thickness are positively associated with thermal protective performance of fabrics. Fabrics with high thickness entrap more air than thinner fabrics, and this air helps to insulate wearers (Sun *et al., 2000*; Torvi & Dale, 1999). However, (Song, et al., 2011) observed that thick fabrics store more thermal energy than thin fabrics in the low intensity radiant heat exposures, and this stored energy may be released due to compression during and after the exposure. The release of the stored energy causes burn injury on a wearer’s skin and consequently lowers the performance of the clothing. (Eni, 2005; Barker, et al., 2006) stated that fabrics may absorb moisture due to perspiration from a sweating firefighter; thus, increasing the thermal conductivity of fibres, and lowering the thermal protective performance of the fabric (Lee & Barker, 1986; Lu, et al., 2013). In contrast, it was also found that if a fabric absorbs a significantly high amount of water (over

15% of its weight), this situation slows down the heating effect to firefighters by reducing the thermal energy transfer (Song, et al., 2011).

(Rossi & Zimmerli, 1996) also investigated the impact of moisture on thermal protective performance of multi-layered fabric systems during hot surface contact. They found that the presence of water in the outer layer of the fabric system (exposed to the hot surface contact) enhanced the thermal conductivity of the fabric system. As a result, the thermal protective performance of the fabric system dropped by 50-60%. In this context, a multi-layered fabric system with a separate moisture barrier in the inner layer exhibited better thermal protective performance than a multi-layered fabric system with a laminated moisture barrier on the outer shell fabric. However, both fabric systems exhibited a similar drop in performance when their inner layers were wet. If the inner layer of the fabric system was wet, the thermal protective performance was found to drop by 10-25% for all of the selected fabric systems, Hence, the decrease in thermal protective performance was greater at lower temperatures because the water accumulated in the fabric layers without any significant evaporation, enhancing thermal conductivity and lowering the thermal protective performance of the fabric systems.

If moisture that has accumulated inside the fabric structure turns into steam during a thermal exposure, the steam may diffuse toward the skin depending upon the fabric's characteristics, leading to skin burns ((Keiser, et al., 2008); (Rossi, et al., 2004); (Keiser & Rossi, 2008). Similarly, water used by firefighters to extinguish fire may generate steam in the environment and thus be transferred through their clothing to produce skin burns. (Rossi, et al., 2004) concluded that water vapor permeability is the most important fabric property to consider for effective protection in steam exposures. They suggested that a water vapor impermeable membrane inside the fabric layers might significantly prevent steam transfer and reduce burn injuries. It was also confirmed that a thick fabric with a water vapor impermeable membrane provides better protection from steam than a thick fabric with a semi-permeable membrane (Keiser & Rossi, 2008); (Sati, et al., 2008).

(Lu, et al., 2013) studied the performance of single-layered fabric systems against hot liquid splash at 85°C. They used water, drilling mud (manufactured by SAGDRIL), and canola oil to simulate various workplace hazards. They observed that the properties of water, e.g., density, thermal conductivity, surface tension, and heat capacity, at 85°C were the highest among all liquids evaluated; whereas, the dynamic viscosity of water was the lowest of all the liquids at this temperature. They found that the thermal protective performance of the fabric systems evaluated depended on the properties of the fabrics (e.g., weight, thickness, air permeability, fibre content, weave structure) and liquids. They found that the air permeability of a fabric system was negatively associated with thermal protective performance under all types of hot liquid splashes. This is an important finding since previous studies did not find any relationship between air permeability and thermal protective performance under flame and radiant heat exposures. (Perkins, 1979) and (Shalev & Barker, 1984) also found that fabric performance was lower when exposed to water or drilling mud than when exposed to canola oil. This was thought to be because the heat capacity of hot-water or drilling mud is higher than the heat capacity of canola oil. Basically, the amount of heat energy per unit mass of hot-water or drilling mud was higher due to their high heat capacity; this high heat content lowered the thermal protective performance of selected fabrics in Lu *et al.'s* study. (Gholamreza & Song, 2013) found that a multi-layered fabric system with an air-impermeable outer layer provided better protection against hot liquid splash than a multi-layered fabric system with an air-permeable outer layer, however garments with impermeable membranes increases the physiological stress of the wearer. Recently, (Lu, et al., 2014). investigated the thermal protective performance of different single-layered fabrics under hot liquid splash. They found that the flow pattern of liquids on the fabrics varied depending on the surface energy between the liquid molecule and fabric. Generally, a very hot liquid or highly rough fabric surface could influence the surface tension of the liquid; in turn, increasing the wettability of the fabric. In the case of a fabric with high wettability, the liquid could penetrate through the fabric due to wicking and cause burns on wearers' skins. (Lu, et al., 2014) further mentioned that the liquid applied can be stored in fabric or transmitted through the fabric depending upon fabric properties (thickness, density, air permeability). If a fabric can store more and transmit less liquid, it will show high initial thermal protective performance. They also found that the addition of a thermal liner with a single-layered shell fabric can help to store more and transmit less liquid and this enhances the performance of the shell fabric.

2.2 Remaining gaps in the previous research

Based on the above discussion, it is evident that much research has focused on the thermal protective performance of multi-layered fabrics used in firefighters' clothing under specific thermal exposures, namely flames, radiant heat, hot surface contact, steam, and/or hot-water splash. From these studies, important fabric properties influencing thermal protective performance under specific thermal exposures and test conditions have been identified (Benisek & Phillips, 1981; Lu, et al., 2014; Rossi, et al., 2004; Rossi & Zimmerli, 1994; Shalev & Barker, 1984). However, no study has evaluated the thermal protective performance of fabrics under all of these thermal exposures, which will be explored in this study. As a consequence, knowledge of the fabric properties that influence thermal protective performance is still limited. Contextually, (Barker, 2005) and (Lawson, 1997) suggested that the studies on thermal protective performance of firefighters' clothing over a wide range of thermal exposures are needed in order to holistically understand the effects of various thermal exposures on the performance. Furthermore, previous researchers focused on the thermal protective performance of fabrics (for industrial use) under hot-water splash conditions (Gholamreza & Song, 2013; Lu, et al., 2013b; Lu, et al., 2013c; Lu, et al., 2014). However, on-duty firefighters are not so likely to be exposed to hot-water splash only. They do kneel and crawl on the floor while working to extinguish fires and rescue fire-victims. While performing these activities, their clothing is compressed specifically in the knees, elbows, and lower-legs, and this will cause a variation in the air gap between the skin and the protective fabric, this variation needs to be analysed and evaluated.

2.3 Textile tests standards norms

Fire-fighter garments must pass an enormous number of tests to reach the required EU standards and norms and CE marking. There are two standards, which are respectively relevant to the field of illuminating and flame-retardant material. The EN 469, Requirements for materials and products to be used by firefighters, and EN 471, Requirements for materials and products to be used as high visibility clothing.

Both these standards contain several references to test methods, which must be used to prove whether the requirements are fulfilled or not. Besides the EN standards, there are several other similar standards, for example the American NFPA 701. The shortcut NFPA stands for National Fire Protection Association, an US organization.

2.3.1 EN 469 protective clothing

The relevant EU-standard for the fire-brigade protective clothing is the DIN EN 469. This standard was published in February 2007. Part 6.14 of EN 469 mentioned about the perceptibility. Optional retro-reflection/ fluorescent materials have to fulfil the requirements in appendix B EN 469. Requirements towards the colour of the fluorescent material always have to correspond to topic 5.1 in EN 471:2003 (Shufei & Schwaiger, 2010).

EN 469 Appendix B.3.1 is about the thermal resistance. The retro-reflecting/ fluorescent materials or materials with combined characteristics have to stand in agreement with section 6.2 EN 469 (requirements of the retro-reflection after mechanical test demand) of the EN 471 (retro-reflection coefficient after the examination), and have to withstand the test-requirements procedure after five minutes. The requirements are mentioned in section 6.5 of the available European standard [i.e. the DIN EN 469]. The EN 469 mentioned that the fabric test-materials have to withstand the test-requirements procedure after five minutes. The results after those five min tests have to be as follows: were suspended, not allowed to drip off, not catch fire, melt or shrink more than 5% (CSN, 2020).

EN 469 Appendix B.3.2 is about propagation of flames. All materials used for perceptibility have to be examined in combination with the external layer after the definitions in topic 6.1 of the EU-standard. This makes it possible to take samples with the measures, which are indicated in procedures A of EN ISO 15025. During and after the testing process, holes in the sample-material are not allowed and not accepted (CSN, 2020).

Within the range of the protective clothing (in the standard EN 469) for firefighters, there are no specific paragraphs especially about phosphorescent material, while fluorescent and reflecting materials are mentioned in the EN 469 for fire-brigade protective clothing as well as in the EN 433 for protective helmets. Within the range of the European standard EN 433 of protective helmets for fluorescent and/or phosphorescing materials, there are no direct requirements but by definition they are trim and accessories (CSN, 2020).

2.3.2 EN 433 accessory

All accessories are additional devices approved by the garment manufacturer, which may be attached to the firefighter helmet and intended to be removable by the user, but which provides no protective function to the wearer. Examples of accessories are lamp brackets, cable clips, badges and trims (Shufei & Schwaiger, 2010).

2.3.3 EN 433 trim

About the trim, there is not so many mentions in the standards. Retro reflective and/or fluorescent material attached to the outermost surface of the helmet shell e.g. for visibility enhancement (Shufei & Schwaiger, 2010).

2.3.4 The old German standard DIN 14940 for helmets

Within the range of the earlier German standard DIN 14940 for helmets (historical document; it was replaced 1997 by the first edition of DIN EN 443). What is interesting here, is that there were already a large number of requirements to the helmet with painting of luminous paint and also the reflex strips.

In the work wear field of high visibility protective clothing, there is a specific norm. The norm EN 471 stands for high visibility. It describes also the use of 3m reflection and shining strips in combination with this fluorescent material but not phosphorescent materials and the special colour of it are mentioned especially (Behrens, 2010).

2.3.5 EN 471 High Visibility

The EN 471, High Visibility standard has two parts, the first part is for the daytime use, and the second part for night-time. During the daytime, fluorescent material in the colour hivis-yellow or Hi Vis-orange is required to give the highest safety under the day-light. The second part is about the reflection stripes of 3m, special stripes that reflect the light. This requirement gives the best safety during night-work. In combination, the 3m reflection stripes and the fluorescent material work together perfectly and give the highest possible security ever. High Visibility material (EN 471) is supposed to be 50 times washable with 60°C. no bleaching, not tumble-drying, no ironing and no chemical cleaning are allowed (Shufei & Schwaiger, 2010).

2.4 Certificates

Next to the EN 469 (protective clothing for fire fighters), every protective garment and textile for European firefighter work wear needs three important certificates: The DIN standard (EN 469 etc.), the CE conformity marking (figure 1) and the GS safety tested standard symbol (figure 2).

The EN 13911 (Requirements and test methods for fire hoods for fire fighters) is one of the important standards (Mehlem, 2006).

Figure 1 CE conformity marking (Shufei & Schwaiger, 2010)

Figure 2 "Geprufte Sicherheit" (safety tested) GS-standard (Shufei & Schwaiger, 2010)

2.5 Flame retardant materials today

Protective clothing has to protect against direct flames, heat contact, radiant heat through steam etc., sparks and also drops of molten metal, and hot and toxic gases. It gives physiological comfort to the person who is wearing it, all the time (Shufei & Schwaiger, 2010).

2.5.1 Definition

A general definition of flame-retardant materials is: "A material capable of limiting the propagation of a fire beyond the area of influence of the energy source that initiated the fire" Actually, at a specific temperature and time, every fabric will start to burn, melt or coal, some faster, some slower. There are natural fibres and materials, which are more resistant towards fire than others. Those that are more flammable can have their fire resistance drastically improved by treatment with fire retardant chemicals (Apparel, 2010).

2.5.2 Materials & producing companies

Nowadays, a lot of different kinds of fibres are used for protective garments. The fibres mentioned below (Nomex®, Kevlar®, PBI, Lenzing FR® and Twaron®) are only example of the wide range of high-performance fibres on the todays market.

LOI (limited oxygen index) is a tool used to measure the level of flame resistance of protective fibres and garments. The higher the LOI, the better the resistance against combustion is. There are three classes of heat protective fibres that can be defined (Zinser, 2009):

- Inherently flame resistant/flame retardant fibres (LOI 18.4 to 20.6, cotton, polyester, viscose fibre to improve the protection, they are finished with flame retardant chemicals);
- Heat-resistant fibres (The LOI is around 25, Nomex® & Kevlar® by DuPont, Conex® & Twaron® by Teijin);
- Aramid fibres (permanently flame retardant, do not melt or drip, compose temperatures between 350-550°C, excellent dimensional stable).
-

2.5.2.1 *Kevlar®/ DuPont*

Kevlar® belongs to the p-Aramids and it is a brand of the DuPont company. Its LOI is 26.0; it is an advanced Aramid-fibre with high heat resistance up to 425°C. No fibre is total heat resistant, from 425°C this fibre starts to char. The important is that it is flame retardant and self-extinguishing, not melting. Furthermore, it has good resistances against cold and chemicals. Fuels, lubricants, synthetic detergents or the salty sea waters do not have influence on Kevlar®. While the latter has an extreme strength, high impact strength, high elongation at break and good vibration dampening. Kevlar is used for special reinforcement on fire fighter garments, but not for the whole garment (Loy & Walter, 2001).

2.5.2.2 *Nomex®/ DuPont*

Nomex® is also a brand of DuPont International; Genf Switzerland and belongs to the m-Aramids which have high temperature resistant fibres and are mainly used for flame retardant cloth and protection against heat. This fibre is used for whole garments. The good properties are ultimate tensile strength, elongation of break and abrasion resistance as Polyamides. It has no melting point, but peculiar it starts to corrode at 370°C and carbonize at 400°C with an ash like the remainder. It gets along with a continuous heating up to 175°C without humidity loss. Between 250-300°C it is still full operational with around 50% of its original fastness. Important is to say, that it is stable against organic chemicals, bleaching agent, alkali, as well as beta- and gamma rays. Concerning its properties Nomex® has got a long durability. The LOI of Nomex® is 24.5. Nomex® is used for technical purpose, flame protection clothing, heat proof sewing threads, filter cloths, parachute, gloves and shoes (DuPont, 2009).

Nomex® On Demand™ is a new smart fibre technology from the DuPont company. This new fibre is breathable, flexible and offers protection against the intrusion of water-based chemicals and viral agents. Its activating point is at 120 °C and can expand 4 to 5 times over its original thickness (DuPont, 2009).

2.5.2.3 *Lenzing FR®*

Lenzing FR® is a special man-made viscose fibre of the Austrian company LENZING AG. Lenzing established in 1892 and in 1976 they developed the Lenzing FR® line. The abbreviation FR stands for “Flame Resistant”. It is a natural fibre derived from wood (figure 3). It offers protection from heat and flame in a variety of different applications for example firefighter garments. Unique thermal insulation properties combined with permanent flame resistance make this fibre a “heat protection fibre”. Its functional properties help to prevent heat stress and heat stroke. Lenzing FR® keeps the body of a firefighter dry and cool, therefore heat stress and heat stroke can be avoided. A further advantage is that Lenzing FR® is a mixture out of the special viscose fibre Lenzing FR® with 50% Aramids (see Table 1) (Torvi, et al., 1999). This gives the best thermal insulation barriers which a fire fighter needs and improves the performance and comfort of 100% Aramids garments. In terms of more sustainability thinking, Lenzing FR® could be a possible option, because this fibre is environmentally friendly. Some more positive arguments for this fibre are: low weight, light resistant, permanent antistatic and it protects the wearer of fire, radiation heat, electronic arc lights (till 10.000 °C), molten metal drops, and flammable liquids (Lenzing, 2008).

Table 1. Possible fibre mixtures with Lenzing FR® (Lenzing, 2008).

Mixtures with Lenzing FR®	
Lenzing FR®	Kermel/ Kermel®
	DuPont/ Nomex®, Kevlar®
	Teijin/ Conex®, Twaron®
	Inter-Tech Group/ PBI®
	Inspec Fibers/ P84®
	MCM/ Basofil®
	wool

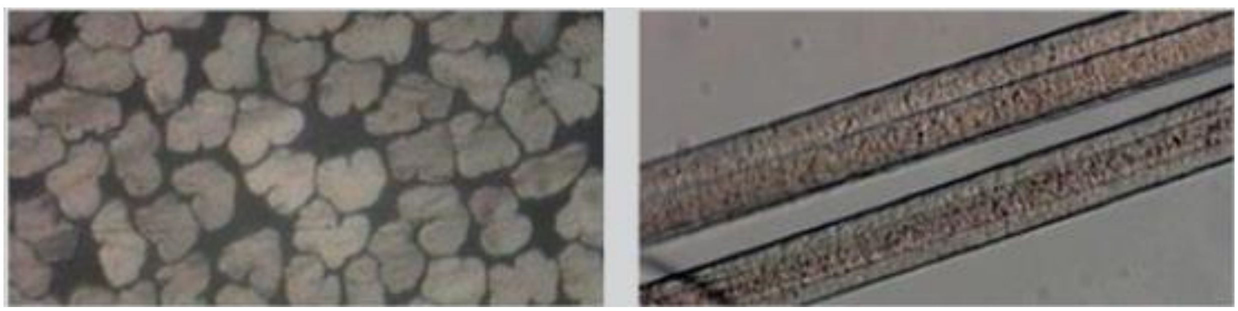


Figure 3 Lenzing FR®, heat protection fibre (Lenzing, 2008).

2.5.2.3.1 Customers and application field

Lenzing has about 10.000 customers worldwide. The product line Lenzing FR is already used in the fields of fire-fighting protective wear, defence protective wear and flame-resistant furniture fabrics.

Some of Lenzing´s partners in the field of safety clothing are Rosenbauer Int. AG and as well Energy AG Austria. In the interview with the fire-brigade commander Mr. Markus Wieshofer from the Austrian fire brigade Alkoven, he mentioned that his brigade is using the mixed quality out of Lenzing FR® and Aramids in all safety clothing for a long time period. Their garments are produced by the company Rosenbauer Int. AG as mentioned above. The Austrian firefighter organization forces the brigades to use the mixed quality instead of 100% aramid-clothing. He said: "The wearing comfort in cold as well in hot working environment is perfect and comfortable for the wearer. Also, he mentioned, that: "The mechanical properties of the garment and also the properties after lot of washings are perfect (Shufei & Schwaiger, 2010).

Further partners are IKEA, TESCO, Marks & Spencer, Adidas, Puma and Nike.

2.5.2.4 *PBI®*

PBI®, known as polybenzimidazole, is a stable organic fibre that provides thermal stability for a range of high temperature applications. PBI® is a product of the InterTech Group.

PBI® is flame resistant, thermal stable, not burning in air and does not melt or drip. Further it retains its strength and flexibility after exposure to flame. The LOI of PBI® is 48 and it is claimed to offer improved thermal and flame resistance, durability, chemical resistance, dimensional stability and comfort in comparison with other high-performance fibres (Shufei & Schwaiger, 2010).

2.5.2.5 *Twaron®*

Twaron® is similar to the Kevlar fibre mentioned above, a high-strength aramid-fibre from the company Twaron Products GmbH, Wuppertal Germany. Twaron® is mainly used for coating fabrics. The thermal stability is distinguished, starting from 425°C degrees, when the material begins to char.

All above mentioned materials are known heat-resistant fibres. Nomex® and Kevlar® already used in the production by FOV fabrics AB. All others could be other possibilities, but especially Lenzing FR® is a sustainable possibility for the future, therefore it is mentioned longer as all others (Loy & Walter, 2001).

2.5.3 Material properties

It can be concluded that a good flame-retardant material must have the following properties (Hes, 2007):

- High abrasion resistance.
- High tensile strength.
- Low dimensional changes.
- Easily washable & fastness of flame resistance.
- Maximum of flexibility and physiological properties in order to prevent heat stress and heat stroke. (Optimum moisture management).
- Low weight.
- high level of flame retardant and resistance and also oil repellence.
- give protection against burns of the skin and avoid radiant heat (Lenzing).

2.6 Field of application of flame-retardant materials

Flame retardant materials have been applied in many different fields; generally, they are classified as follows (Mattila & Heikki, 2009):

- Firefighter’s protective clothing,
- Fabrics for the military,
- Aerospace and aviation field,
- Maritime and naval applications,
- Metal-melting-industry,
- Energy-industry workwear, etc.

Chapter 3: Finite Elements Modelling and Validation with Tests

3.1 Finite elements modelling

A typical firefighters' protective clothing model system is shown in Figure 4. The numerical model has been used to determine the temperature profile within the fabric and the skin layers. The proposed model is based on a nonlinear finite element analysis, including temperature-dependent material properties and suitable boundary conditions. The model is reproduced at small scale, see Figure 4, based on experimental tests, usually developed to evaluate the performance of protective garments subjected to heat and fire, when testing material assemblies exposed to a source of radiant heat (British standards: 6942,2002).

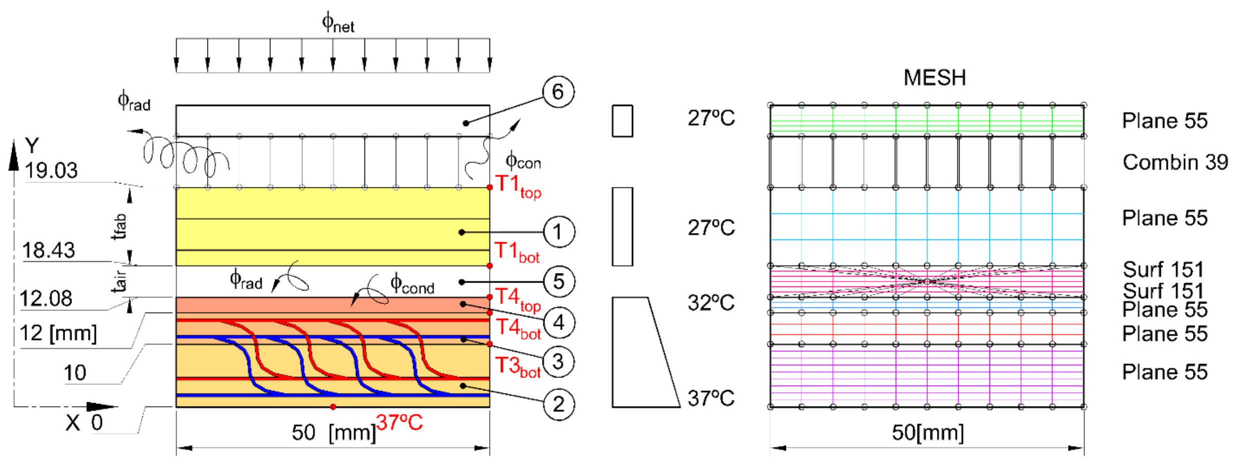


Figure 4 Two-dimensional garment-skin model (left) and finite element mesh (right).

This model includes the region for fabrics, skin and air gap between both. The model also presents the boundary conditions, in particular the effect of the blood perfusion in the layer number 2 (subcutaneous) and number 3 (dermis).

3.2 Heat transfer throughout the system

The model considers the skin-garment assembly as a system featuring three layers of human skin (epidermis, dermis, and subcutaneous), and an air gap between the fabric and the skin, as depicted in Figure 4 and table 2. The protective garment is submitted to a heat flux of 83 [kW/m^2] for 10 seconds, reflecting 9%. It is assumed that after 10 seconds of exposure, there will be a shielding system to vanish the incoming heat flux. The net heat flux will be applied on the top of the special material model (6) (modelled with PLANE 55, Four nodes with one DOF). The heat flows by conduction through this special material (high conductivity and low heat capacity), using the auxiliary element to deliver heat by conduction (COMBIN 39 , Two nodes and up to three DOF) to the exposed surface of protective garment (1) (modelled with PLANE 55). The exposed surface is subjected to radiative and convective heat losses to its surroundings (27ºC). At the same time, heat flows through the fabric and delivers heat into the region of the air gap (5) (by radiation and conduction), using special interface surface elements (SURF 151, Two to five nodes with one DOF) and normal plane finite elements (PLANE 55). Heat flows to the skin layers, passing through the epidermis (4), following to the dermis (3) and subcutaneous (2) layers, assuming the effect of the blood perfusion rate (Rai & Rai, 1999). This effect is responsible for the heat generation in these regions when the temperature is below 37ºC, may also act in heat evacuation, when the temperature of the skin is above this value. Normal body core temperature must be close to 37ºC to maintain the human body in health state.

Table 2 Finite elements used in the model's layers

System layers	Heat transfer methods	Finite elements
1. Fabric (Kevlar/PBI)	Conduction	PLAN55
2. Subcutaneous layer	Conduction	PLAN55
3. Dermis layer	Conduction	PLAN55
4. Epidermis	Conduction	PLAN55
5. Air gap	Conduction + Radiation	PLAN55(cnd) + SURF151(rad)
6. Special layer	Conduction	PLAN55

A non-linear transient thermal analysis is developed, during the heating phase and cooling phase to solve the energy equation (Eq. 1).

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+w_b.C_{pb}\left(T_a-T\right)=\rho.C_p.\frac{\partial T}{\partial t} \tag{1}$$

The temperature field (T) is determined in each domain and compared with experimental results for validation (Ghazy & Bergstrom, 2010). The 3rd parcel on the left-hand side applies only to the dermis and subcutaneous regions, assuming the arterial temperature T_a=37 ºC. All the other thermal properties depend on the region where the heat flows by conduction, being λ the thermal conductivity, C_p the specific heat and ρ the specific mass.

The finite element solution requires an incremental and iterative solution, based on a time step of 60 s, with the possibility to be reduced to 1 s, depending on the convergence criterion defined by the heat flow, based on a tolerance value of 10^{-3} and a reference value of 10^{-6}.

Dirichlet and Newmann boundary conditions should be applied in the external regions of the domain, in particular in the bottom surface from the subcutaneous region and on the top surface of the protective garment, respectively. The loss of heat by convection is governed throughout the convection coefficient h_c, which depends on the velocity of the surrounding air gas above the protective garment. This coefficient is assumed for free convection of a cooled plate facing upward (Holman, 2010), given by:

$$h_c=0.59\left(\left(T_{fab}-T_{amb}\right)/t_{fab}\right)^{1/4} \tag{2}$$

The loss of heat by radiation depends on the material emissivity, gas emissivity and the ambient temperature T_{amb} taken as 300 K. The initial temperature in each region is defined according to Figure 4.

Most of the material properties are temperature dependent and some are combined to represent the air voids in fabrics. The numerical model is validated with a protective garment made with Kevlar/PBI. The thermal properties for Kevlar/PBI are based on experimental measurements from Torvi (Torvi, 1997) using an emissivity of 0.9, the thermal properties for the air layer are based on experimental measurements from (Çengel & Ghajar, 2015) and the thermal properties for the human skin are assumed constant, as mentioned in (Ghazy & Bergstrom, 2010), assuming an emissivity value of 0.98 for the epidermis.

3.3 Material thermal properties

The materials (Kevlar/PBI, Nomex and air) included temperature dependent thermal properties (see figure 5). The fabrics apparent heat capacity C_p has been measured using a differential scanning calorimeter (DSC) and then modelled as a function of the fabric temperature. It includes the evaporation of the fabric moisture content and the fabric thermal degradation. The fabrics specific heat is calculated as (Torvi, et al., 2006):

$$C_p = 1300 + 1.6\,(T - 300K) \qquad (3)$$

The fabrics thermal conductivity is determined from the fibre to air fraction of the fabric as follows (Ghazy & Bergstrom, 2010):

$$k(T) = 0.8K_{air}(T) + 0.2K_{fbr}(T) \qquad (4)$$

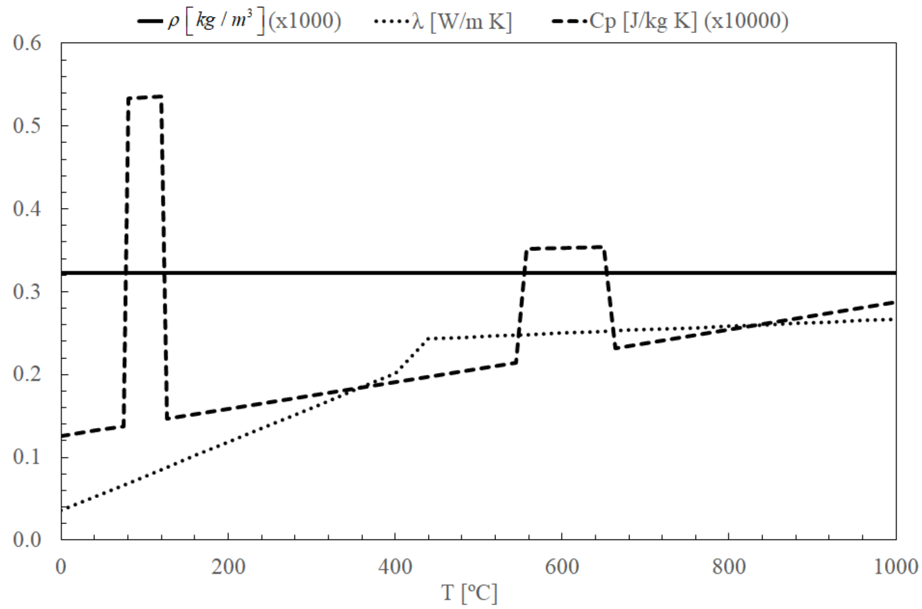
where K_{air} is the thermal conductivity of the air contained in the fabric's pores and K_{fbr} is the fibre thermal conductivity, both are defined as (Ghazy & Bergstrom, 2010):

$$k_{air}(T) = 0.026 + 0.000068(T - 300K) \qquad T \leq 700K \qquad (5)$$

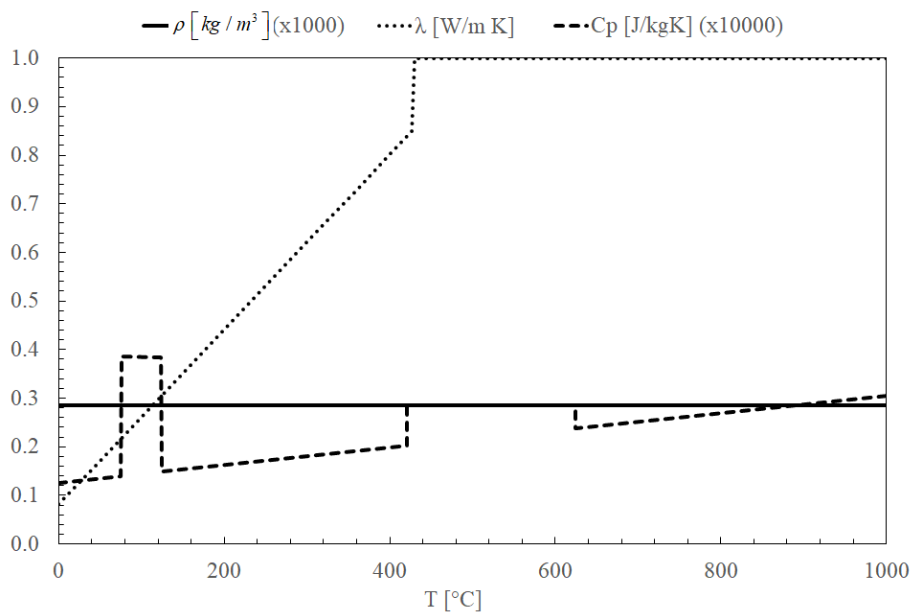
$$= 0.053 + 0.000054(T - 700k) \qquad T > 700K \qquad (6)$$

$$k_{fbr}(T) = 0.13 + 0.0018(T - 300K) \qquad T \leq 700K \qquad (7)$$

$$= 1 \qquad T > 700K \qquad (8)$$



a) Kevlar/PBI



b) NOMEX

Figure 5 Temperature dependant thermal properties of the fabrics: a) Kevlar/PBI, b) NOMEX.

The thermal properties for Air are depicted in figure 6 (Çengel & Ghajar, 2015)

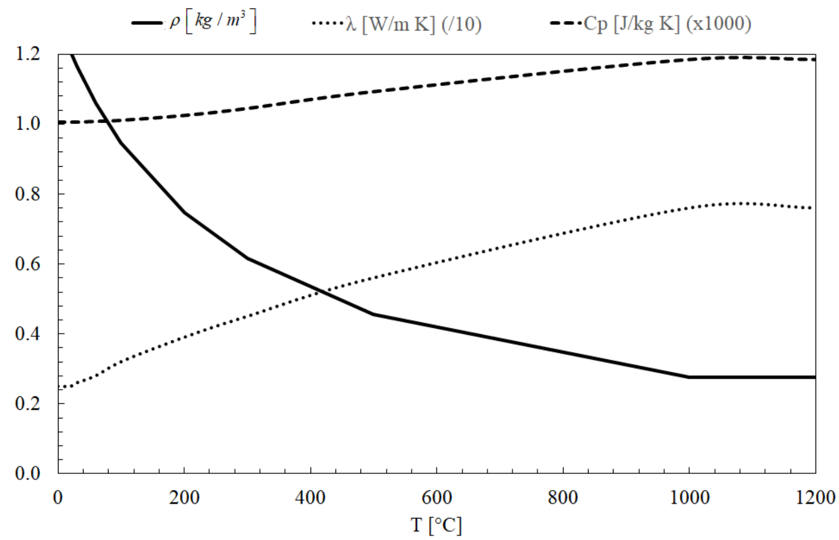


Figure 6 Temperature dependent thermal properties of air (Çengel & Ghajar, 2015).

Table 3 considers the main thermophysical properties for the human skin (Ghazy & Bergstrom, 2010). Constant values were considered. The emissivity of clean human skin is a result of many studies done during a time period of 30 years (Bernard, et al., 2013).

Table 3 Human skin thermophysical properties (Bernard, et al., 2013)

Property	Epidermis	Dermis	Subcutaneous
Density [kg/m^3]	1200	1200	1000
Specific Heat [J/kgK]	3598	3222	2760
Conductivity [W/mK]	0.255	0.523	0.167
Emissivity	0.98		
Thickness [mm]	0.08	2	10

The blood perfusion rate W_b remains constant until the tissue temperature exceeds a critical value T_{cr} =42.5 ºC and increases linearly with temperature up to T_{max}=45ºC (Rai & Rai, 1999).

This effect is included by the heat generation (heat removal) boundary condition, corresponding to 3rd parcel in Eq. 1, see Figure. 7.

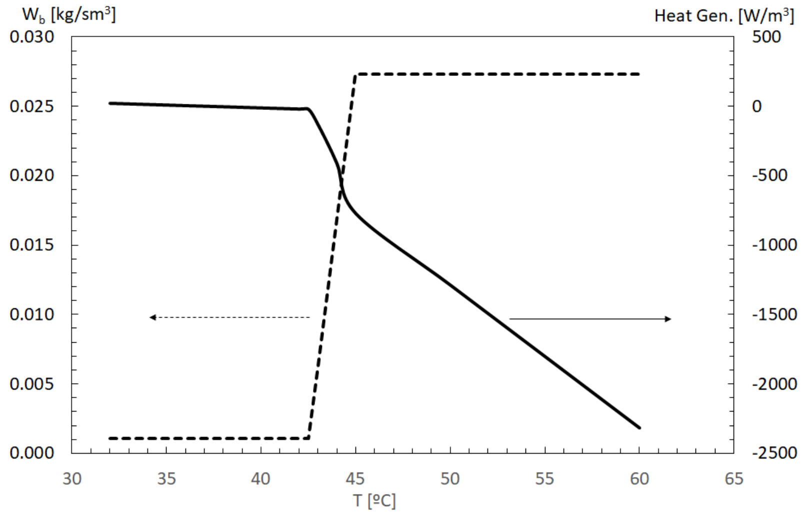


Figure 7 Temperature dependent blood perfusion rate.

3.4 Results validation and skin burn prediction

The results used for validation are presented in Figure. 8, considering one single layer for the protection garment (KEVLAR/PBI) with 0.6 mm thick, an air gap with a standard thickness of t_{air}=6.35 mm and a three-layer model for skin (epidermis with 0.8 mm, dermis with 2 mm and subcutaneous with 10 mm). The numerical results for $T4_{BOT}$ and $T3_{BOT}$, obtained with this model, agree well with experimental tests and with the numerical results from other authors (Ghazy & Bergstrom, 2010).

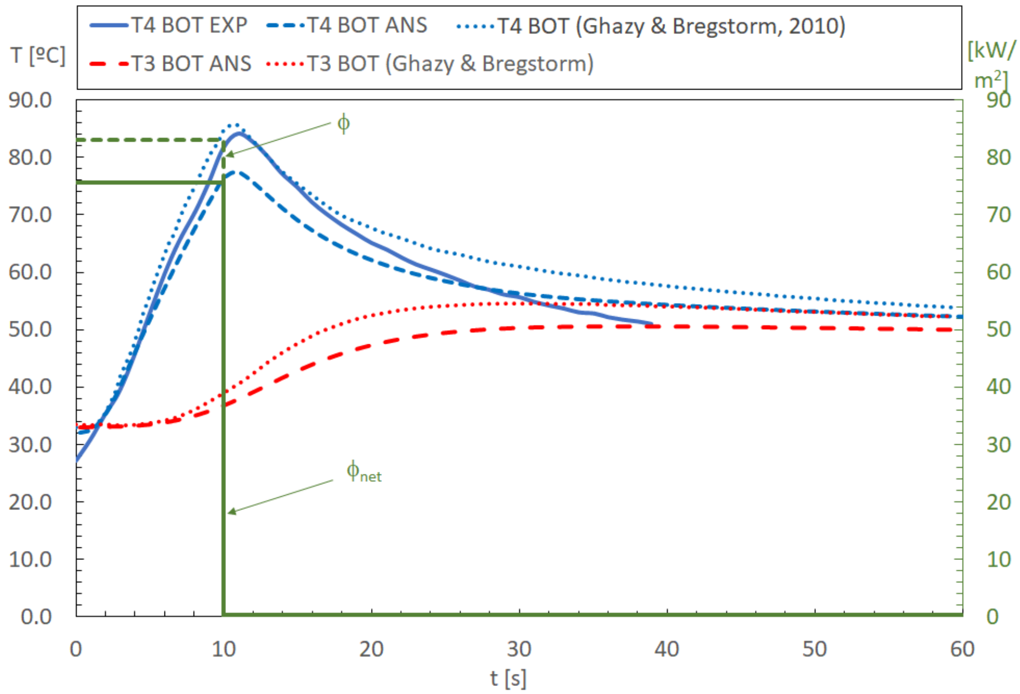
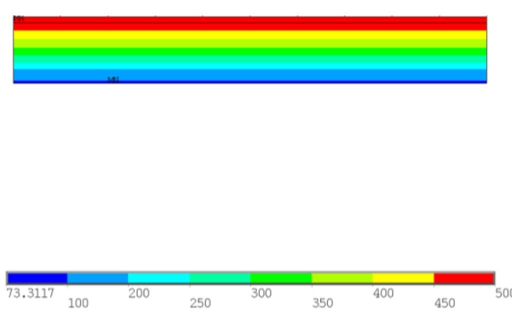
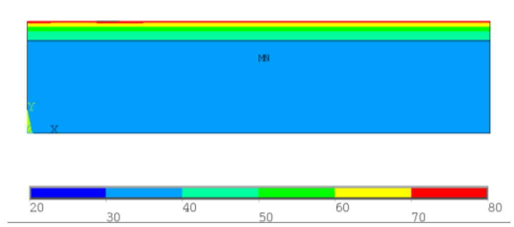


Figure 8 Temperature on basal layer (T4BOT) and dermal base (T3BOT), with Kevlar/PBI protection.

The temperature field is depicted in Figure 8 for the most important zones of the model, specifically for the time corresponding to the maximum temperature obtained on the basal layer. The temperature of the protection layers is represented on the Figure 9 (a) and the temperature on the three-layers skin model is represented in the Figure 9 (b). The temperature on the subcutaneous region is below 40 ºC.



a) Temperature on fabrics and air layer



b) Temperature on the three-layered skin.

Figure 9 Temperature field for the simulation time 12 s (skin protected with Kevlar/PBI, exposed to the heat flux of 83 KW/m2, during 10 s).

Epidermis and dermis may be submitted to elevated temperatures and its behaviour depends on the heat flux and exposure time. The more a thermal exposure exceeded the threshold required for destruction of the epidermis, either in respect to temperature or time, the deeper the injury and the longer is the time required for repair and regeneration (Moritz, 1947).

The first-degree burn (t1) is characterized by a dilatation of the superficial vessels sufficient to cause visible reddening of the skin, usually followed, by the damage to the epidermis (see figure 10). Generally, no blister occurs in such burns, and discomfort is temporary.

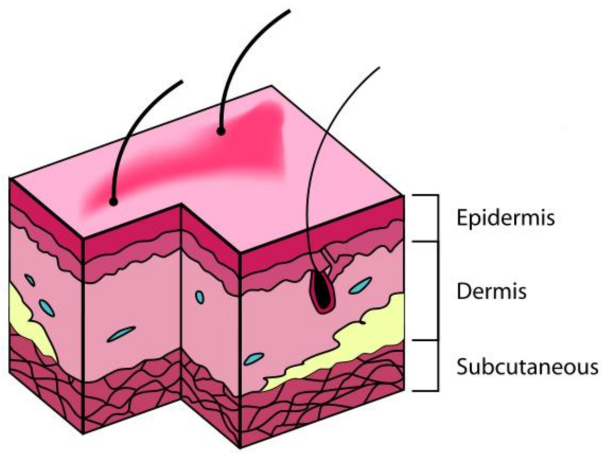


Figure 10 First degree burn (Aainsqatsi, 2007)

The second-degree burn (t2) depends on the time-temperature characteristics of the basal layer, just sufficient to cause transepidermal necrosis. Second-degree burns mainly occur on the epidermis and dermis layers. Such burns can also be classified as superficial and deep. Healing is normally prompt with no scars because the majority of the cells at the dermal base are unaffected. Deep second-degree burns affect the dermis, the capillaries or blood vessels may be affected. This situation causes tissue oedema and blisters on the skin as shown in figure 11.

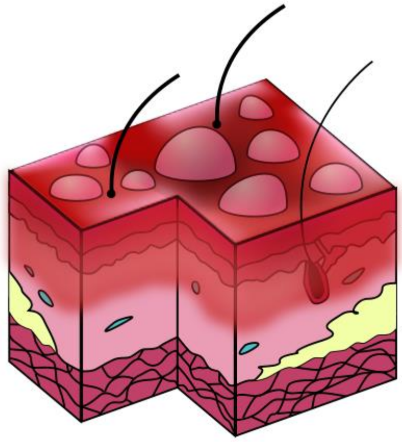


Figure 11 Second degree burn (Aainsqatsi, 2007)

The third-degree burn (t3) depends on the temperature assessment of the dermal base. Both the epidermis and dermis layers are damaged. Trauma to the blood vessels occurs, eliminating the blood flows and the cells start to die. It is very difficult to recover from this type of burn as can be seen in figure 12 (Song, et al., 2017).

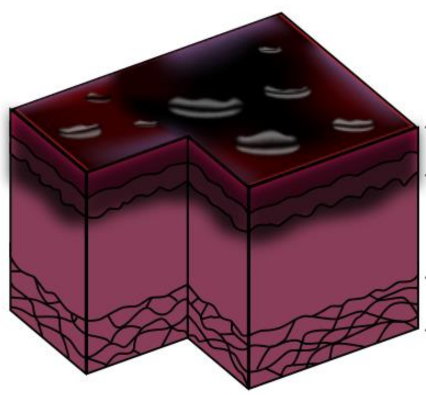


Figure 12 Third degree burn (Aainsqatsi, 2007)

The burn damage of the skin may be calculated using Henrique's burn integral equation (Henriques Jr & Moritz, 1947), which can be expressed according to (Eq. 9). The values for the pre-exponential factor P and the activation energy ΔE may be obtained for the first-degree, second-degree and for third-degree burn injury (Song, et al., 2017) (see table 4).

$$\frac{d\Omega}{dt} = \begin{cases} 0, & T < 44°C \\ Pe^{-(\Delta E/RT)}, & T \geq 44°C \end{cases} \quad (9)$$

To develop this skin burn model, time should be considered when the temperature of the epidermis is above 44°C (Eq. 9). This equation should be further integrated, where, Ω is a quantitative measure of burn damage at the epidermis or at any depth in the dermis (dimensionless). Table 3 presents the values used for the pre-exponential factor P (s^{-1}) and the activation energy for human skin ΔE (J/mol). The universal gas constant R should be consider equal to 8.315 (J/kmol K), T is the absolute temperature (K) at the basal layer for t1 and t2 prediction, but for the t3, the temperature of the dermal base layer (K) should be considered instead, and t is the total time for which T is above 44°C (s) (Song, et al., 2017).

The first (t1) and second-degree (t2) burns occur when T is determined for the basal layer and Ω reaches 0.53, and 1, respectively. The third-degree burn occurs when T is determined for the dermal base layer and Ω reaches 1. According to the skin burn criteria applied to the validation model, the 1st degree burn is achieved at 6.36s and 2nd degree immediately after. The time history of the dermal base temperature (T3BOT) is relatively different, continuing to increase during the period of no external heat flux, causing no third-degree burn or sometimes predicting it very late. The differences between results may be explained by the assumption used to the material properties and to the boundary conditions.

Table 4 Pre-exponential factor and ratio of activation energy (Song, et al., 2017).

Property	Temperature [ºC]	Epidermis	Dermis
P [s^{-1}]	$44 \leq T < 50$	1.185×10^{124}	4.32×10^{64}
P [s^{-1}]	$T \geq 50$	1.823×10^{51}	9.39×10^{104}
$\Delta E/R$	$44 \leq T < 50$	93534.9	50000.0
$\Delta E/R$	$T \geq 50$	39109.8	80000.0

Chapter 4: Parametric analysis results and discussions

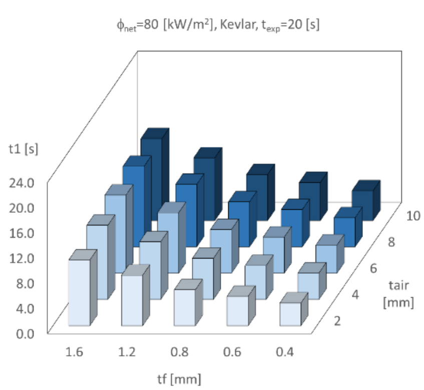
4.1 Parametric analysis

A parametric analysis was developed upon a set of 500 simulations for the following parameters:

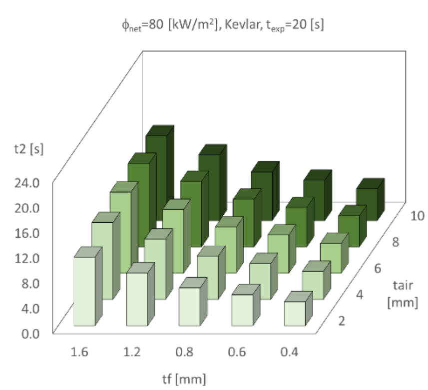
- Air gap thickness t_{air}= 2, 4, 6, 8 and 10mm;
- Protection garment using Nomex and Kevlar/PBI;
- Fabric thickness t_{fab}= 0.4, 0.6, 0.8,1.2 and 1.6mm;
- Net heat flux level ϕ_{net}= 10, 15, 25, 40 and 80 kW/m^2.

All simulation were developed with a fire exposure time of 10s and 20s, followed by a cool-down period of 60s.

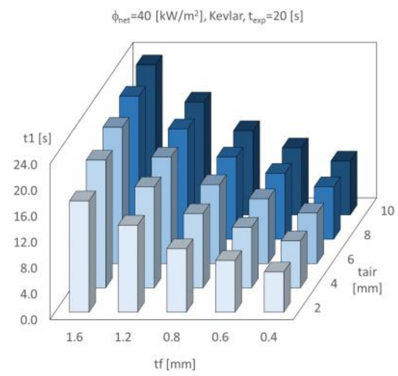
Figure 13 shows the skin burn prediction (t1 and t2) for different air gap and protection fabric thicknesses. The protection material is Kevlar/PBI and results are presented for medium (40 [kW/m^2]) and high heat fluxes (80 [kW/m^2]), and for an exposure time of (t_{exp}=20 s). The effect of other net heat fluxes is also depicted in the histograms below.



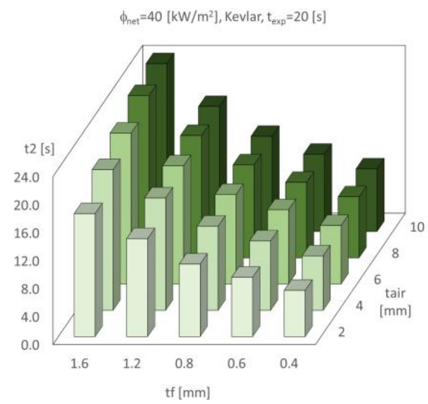
a) t1 for a net heat flux of 80 kW/m^2.



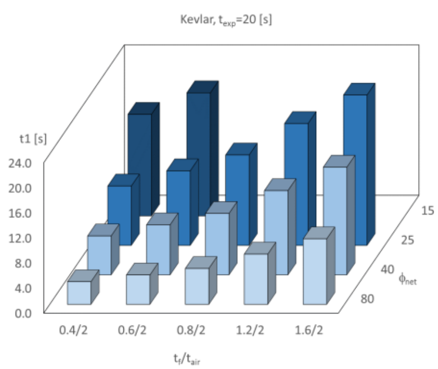
b) t2 for a net heat flux of 80 kW/m^2.



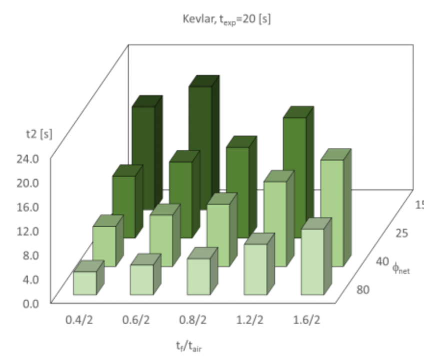
c) t1 for a net heat flux of 40 kW/m^2.



d) t2 for a net heat flux of 40 kW/m^2.



e) t1 depending on net heat flux

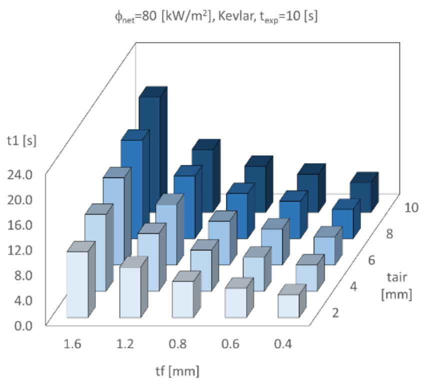


f) t2 depending on net heat flux

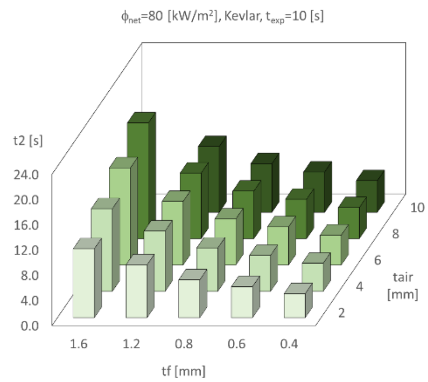
Figure 13 Skin burn predictions (t1 and t2) for Kevlar/PBI protection.

The results show that the time for the t1 and t2 skin burn depends on the heat flux, as expected. When the fire protection material is exposed to higher heat fluxes, smaller time is required to achieve the first (t1) and second-degree burn (t2). The time t1 and t2 also decreases with the decrease of the air gap and with the decrease of the fabric thickness. The third-degree burn (t3) is reached during the cooling down period for all the simulations developed under the net heat flux of 80 kW/m^2 and only occurs for the heat flux of 40 kW/m^2 under low thermal resistance ($t_{air} \leq 4$ mm and $t_f \leq 0.6$ mm).

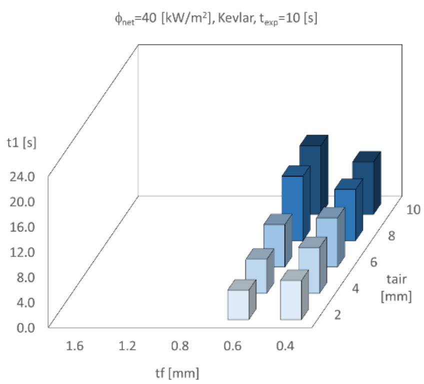
Similar results were achieved for smaller exposure time when using Kevlar/PBI. Figure 14 shows the skin burn prediction (t1 and t2) for the same testing conditions, under smaller exposure time (t_{exp}=10 s). The time t1 and t2 also decreases with the decrease of the air gap and fabric thickness. In certain condition, the first-degree burn and the second-degree burn is reached during the cool down period, especially for the combinations of higher thermal resistance (higher thickness of air gap and fabric), such as when $t_{air} \geq 4$ mm and $t_f = 1.6$ mm.



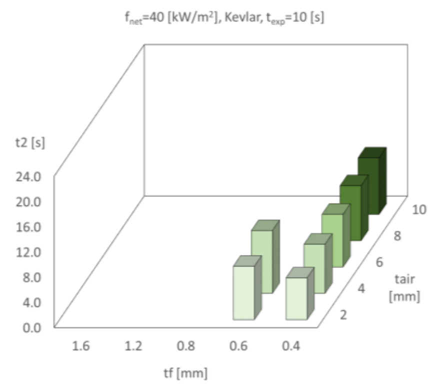
a) t1 for a net heat flux of 80 kW/m^2.



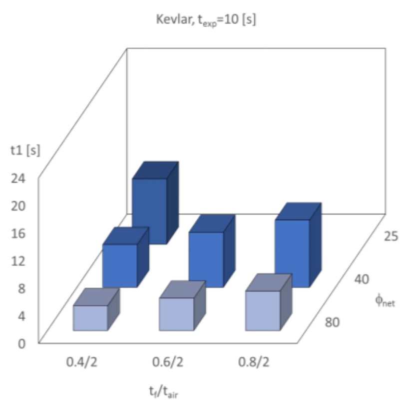
b) t2 for a net heat flux of 80 kW/m^2.



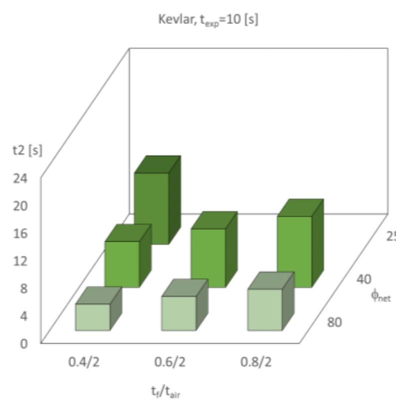
c) t1 for a net heat flux of 40 kW/m^2.



d) t2 for a net heat flux of 40 kW/m^2.



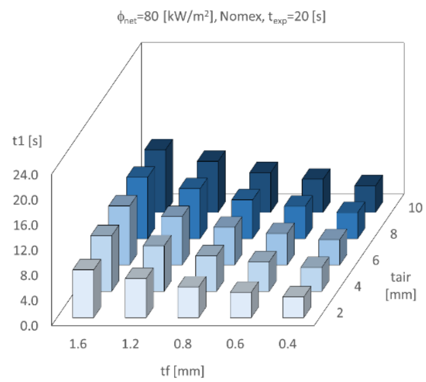
e) t1 depending on net heat flux



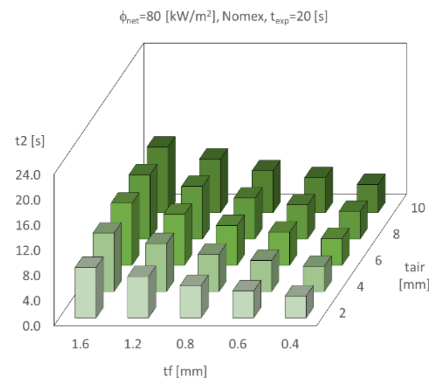
f) t2 depending on net heat flux

Figure 14 Skin burn predictions (t1 and t2) for Kevlar/PBI protection.

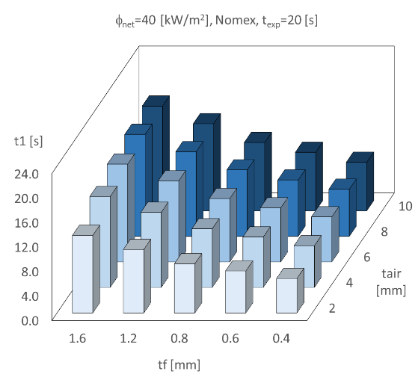
The same simulations were performed using Nomex. This material offers smaller fire protection. The time to reach t1 and t2 is smaller for every combination of heat flux, air gap and fabric thickness. This conclusion may be justified by the higher conductivity of this material under elevated temperatures. Results are only presented for higher exposure time (t_{exp}=20 s), see Figure 15.



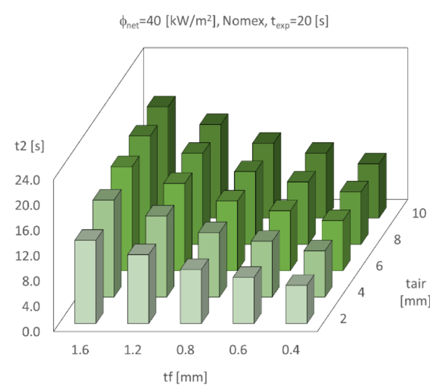
a) t1 for a net heat flux of 80 kW/m^2.



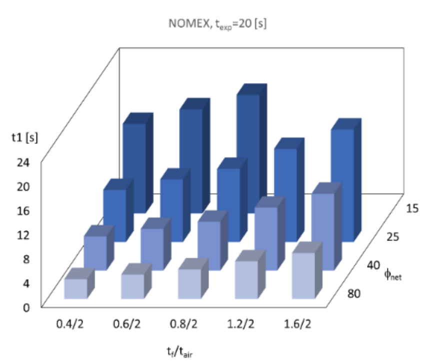
b) t2 for a net heat flux of 80 kW/m^2.



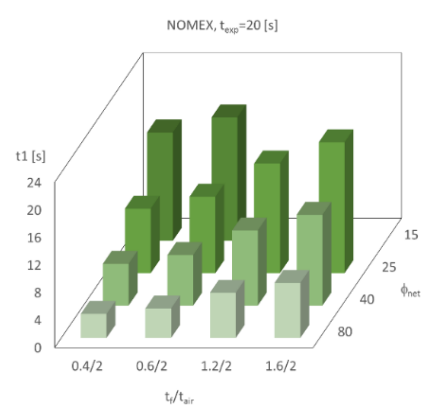
c) t1 for a net heat flux of 40 kW/m^2.



d) t2 for a net heat flux of 40 kW/m^2.



e) t1 depending on net heat flux

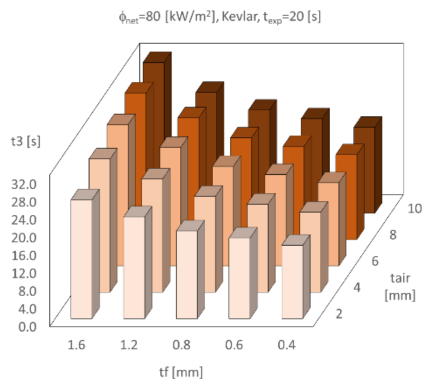


f) t2 depending on net heat flux

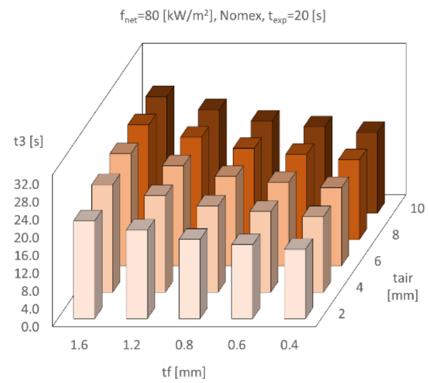
Figure 15 Skin burn predictions (t1 and t2) for Nomex protection.

All combinations tested under 80 kW/m^2 reached the third-degree burn. This skin damage was also achieved for certain conditions under 40 kW/m^2 (usually for lower thermal resistance).

Figure 16 compares the results for the third-degree burn of both fabrics, for the net heat flux of 80 kW/m^2 and for higher exposure time (t_{exp}=20 s). Firefighters using Nomex should expect to reach the third-degree burn in a shorter period.



a) t3 for Kevlar/PBI and net heat flux of 80 kW/m^2.



b) t3 for Nomex and net heat flux of 80 kW/m^2.

Figure 16 Skin burn predictions (t3) for Kevlar/PBI and Nomex protection

4.2 Effect of air gap thickness

Garment fit is a crucial factor in the design of thermal protective clothing as it decides flexibility for body movement as well as the amount of air gap between clothing and skin. Air gap between garment and skin surface provides additional protection to the first responders. As air gap increases, the heat flow by conduction through the air gap decreases and total heat transfer to the skin decreases till the critical air gap because up to these values (2mm ~ 10mm) the air gap width is not sufficient to start natural convection. initially the second degree burn time increases rapidly and then slowly with increase of air gap width.

What is interesting in our model is that when using the KEVLAR/PBI fabric for the garment, the time for third degree burn is only recorded with an air gap of 2mm at $t = 22.63s$, which means that the third-degree burn is reached in the cool-down period.

4.3 Effect of fabric thickness

As fabric thickness increases, its thermal resistance increases and therefore the skin burn degrees time and TPP increases. In fact, the thickness is the primary factor which governs heat transfer through fabrics in case of radiant heat as well as in case of combined convective and radiant heat exposures. Skin injurie did not reach a 3rd degree burn for fabric thicknesses greater than 1.2mm, due to the increase in the thermal resistance of the fabric. On the other hand, the 1st and 2nd burn degree times seem to be almost linear with variation of the fabric thickness.

4.4 Effect of exposure intensity

Heat transfer through fabrics is affected by the intensity of the exposure, hence, thermal protective performance of the fabrics varies depending on the exposures, this variation will have a significant effect on the skin burn predications. It can be observed from figure 13 (e & f) that the times to skin burn degrees injuries is significantly different, even when using the highest fabric thickness value. The time to first degree burns under an exposure of 40 KW/m^2 is 6.7s, smaller than time to first degree burn under an exposure of 80 KW/m^2. The same conclusion can be presented to r the second-degree burn, where the difference was 6.75s. The same behaviour can be noticed when looking to data from other parameters (10s exposure time, with Nomex fabric).

4.5 Effect of fabric thermal properties

Different materials have different thermal properties, and properties of fabrics change not only due to progressive deterioration during use but also during the thermal insulate of fabrics to heat exposure. These functional changes may severely affect thermal properties necessary for better protective performance of fabrics. It has been observed that thermal conductivity plays important role in thermal protective performance. In addition to these properties, the heat capacity of fabric layers also plays important role in case of short duration, high intensity heat exposures. As thermal conductivity of fabric increases, heat transfer rate increases and the skin burn degrees injuries time decreases. There can be situations when skin burn is caused by energy stored within the fabric, even after the end of exposure, rather than the heat transferred during the exposure especially at lower heat exposure conditions.

Specific heat capacity is the measure of heat storage in the fabrics. As fibre specific heat capacity increases, stored energy within the fibre increases resulting in less heat transfer through fabric to the skin. Hence, time to skin burn degrees increases. Therefore, choosing the right fabric to make a protective clothing for firefighters is crucial. In this study, two fabric types have been analysed (Kevlar/PBI and Nomex). Figure 17 provides a comparison between the two fabric performances under 10s of 80KW/m^2 radiant heat exposure. With a fixed fabric thickness of 0.6mm, the Kevlar/PBI is performing much better thermal insulation then Nomex fabric, where in small air gap sizes, Nomex fabric allowed the third-degree burn injury to reach the skin unlike Kevlar/PBI, that's because Nomex is more heat conductive than Kevlar/PBI.

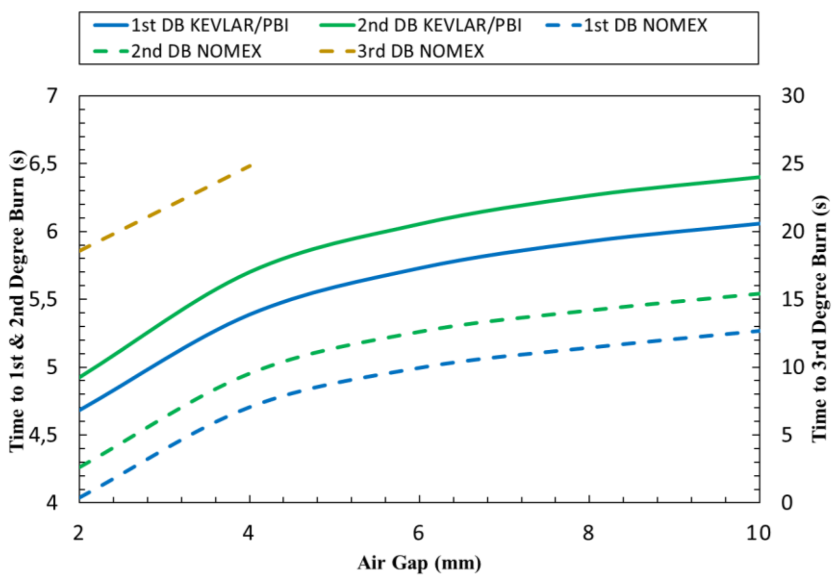


Figure 17 Performance comparison between Kevlar/PBI and Nomex 10s of 80KW/m2 radiant heat exposure.

4.6 A skin burns prediction proposal

Based on the numerical results determined for high flash fire (80kW/m^2) and for high exposure time (20 s), a new proposal is presented to determine the time to reach the first, second and third-degree skin burn. This approximation is presented for both protective materials (Kevlar/PBI and Nomex). The approximation intends to minimize the sum of the square residuals (SSR) between the numerical results and the approximation. The solution method is based on a nonlinear optimizing solver. The approximation formula is presented in the Eq. 10 and the parameters A, B, C and D are presented in table 5. The sum of the squared residuals (SSR) is also determined.

$$t = A \times t_f + B \times t_{air} + C \times t_f \times t_{air} + D \qquad (10)$$

Table 5 New coefficients proposed for the prediction of the skin burn.

Material	Kevlar /PBI					Nomex				
Time	A	B	C	D	SSR	A	B	C	D	SSR
t1	5.63	0.08	0.14	1.2	1	3.49	0.06	0.14	1.89	1
t2	5.83	0.10	0.13	1.30	1	3.66	0.07	0.14	2.0	1
t3	7.97	0.11	0.42	13.10	11	5.23	0.24	0.15	13.32	4

Chapter 5: Conclusions

5.1 Conclusions and future research work

Significant research has been done in the field of thermal protective clothing. The important research investigations dealing with various aspects of the thermal protective clothing are reviewed in the present work. Standards related to the thermal protective performance of fabrics are presented. Effects of various structural and physical parameters related to fabric as well as parameters associated with the external environmental conditions on the protective performance of fabrics are discussed in detail.

A finite element model for transient heat transfer in firefighters' protective clothing has been developed. The model accounted for the combined conduction-radiation heat transfer in the air gap between the clothing and the skin.

The validation of a numerical model was obtained from experimental tests developed on a bench test according to ASTM D 4108, using a skin simulant material. After the validation, a set of numerical simulations were developed to analyse the effect of several parameter (type of protection garment, thickness of the protection garment, heat flux, air gap, and exposure time) on the sin burn prediction.

The influence of the air gap can be described as the wider the gap is, the longer it takes to reach a skin burn degree, due to the increase in the thermal resistance. On the other hand, the study explored various approaches to reduce heat transfer through the air gap and the fabric and, therefore attempted to improve the overall performance of the garment. The numerical results suggest that heat storage can be enhanced when the gap thickness between the skin and the textile garment is important. The higher thicknesses for both the better to avoid third degree burn. Three parameters (thickness, intensity of net heat flux and time exposure) were used to evaluate the thermal behavior of the skin surface before and during post-fire exposure. The influence of these parameters on air-gap width, heat source and garment thickness were investigated and compared with the Henrique's model. With increasing intensity of the heat source, obviously will reduce the time to first-degree burn. Thicker garments had monotonically increased the time of the first burn injury and gradually decreasing the maximum basal layer temperature. The air gap was a reasonable buffering layer owing to increase thermal resistance.

$T3_{bot}$ rose gradually at the beginning of the cooling time, denoting that the skin burn injury depends not only on the transferred energy during exposure but also on the discharge of the stored thermal energy after exposure.

Based on the results of this study, the best protective performance of firefighter's garment can be obtained by considering the structure parameters that seem to be more important than thermophysical parameters in terms of thermal protective performance (TPP). Therefore, the structure of the garment and the air gap width should be first considered.

This research also presents a new proposal for the prediction of the time to achieve the skin burn injury related with first, second and third degree burn for the worst exposure condition.

Accurate modelling of heat and moisture transfer through fabrics demands knowledge of accurate thermo-physical and radiative properties of the fabrics of all three layers. When exposed to high heat flux, fabric encounters very high temperature and thermophysical properties of fabrics change significantly. Thermophysical and radiative properties of fabrics depends on structural parameters, shrinkage, pyrolysis as well as moisture content of the fabric. Estimation of thermo-physical and radiative properties of fabrics and effect of above-mentioned parameters on the properties are the areas which need urgent attention.

This thesis demonstrates the importance of accurately modelling the air gap entrapped in firefighters' clothing. Neglecting the air gap entrapped between the clothing and the skin would dramatically underestimate the protective performance of the clothing. The thesis, in a general context, contributes to the knowledge of combined conduction-radiation heat transfer in enclosures filled with radiation participating media and bounded with high temperatures and heat fluxes conditions.

To shed light on the future research, many experimental and numerical studies have been reported in the literature to understand complex phenomenon of heat and moisture transfer through the thermal protective clothing. However, studies show that much attention have given only on heat transfer models rather than simultaneous heat and moisture transfer models. There is lack of systematic understanding of moisture on thermal protective performance of fabrics for heat exposures of different types and intensity which need to be explored further. Further numerical and experimental research are required to understand simultaneous heat and moisture transfer mechanism.

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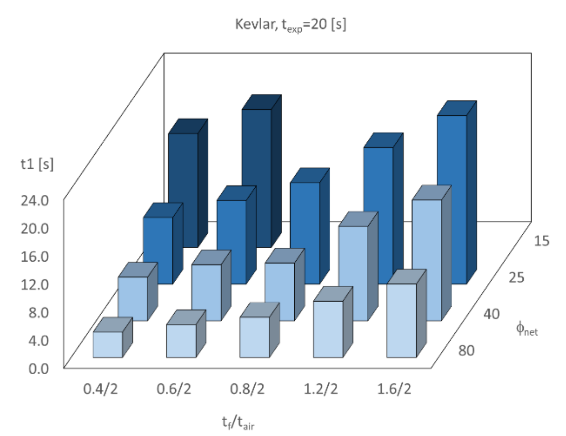
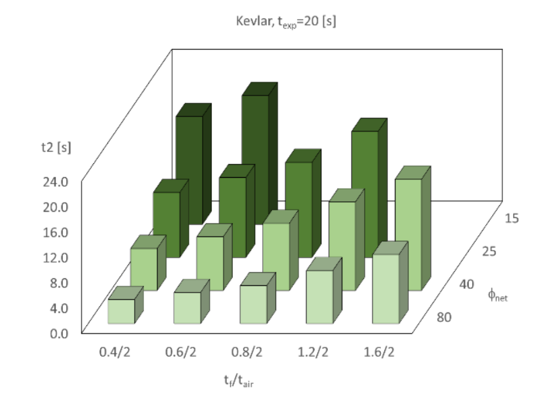
Appendices

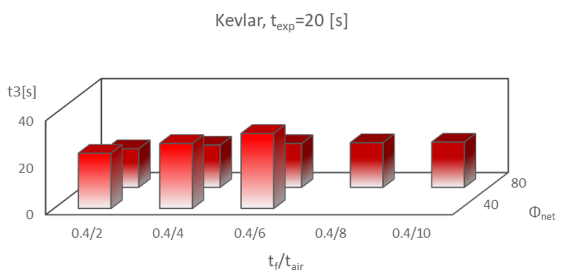
Appendice.1: t1, t2 and t3 results for Kevlar fabric with an exposure time $t_{exp} = 20s$.



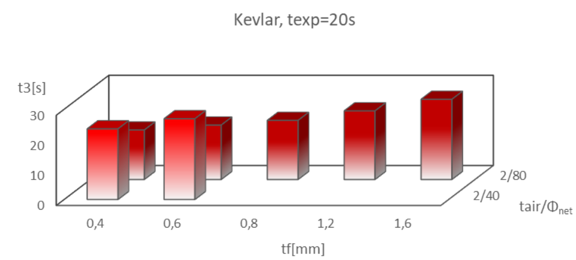
a) 1st degree burn depending on net heat flux.



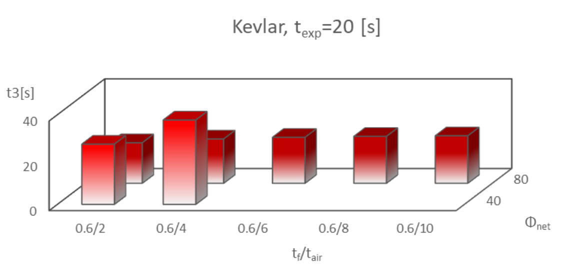
b) 2nd degree burn depending on net heat flux.

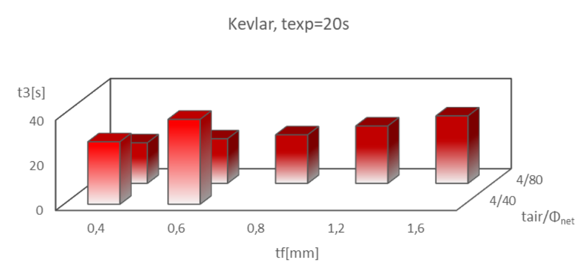


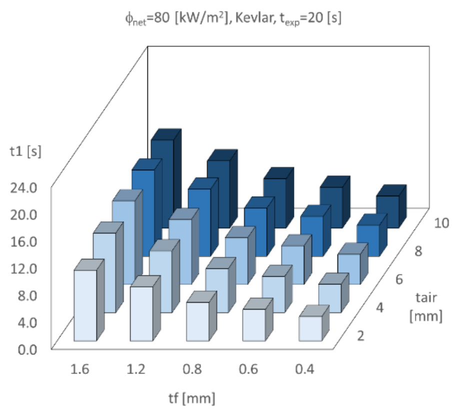
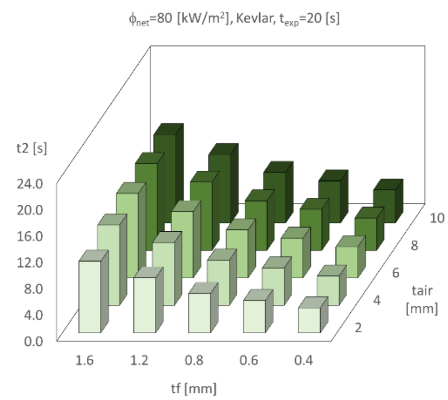
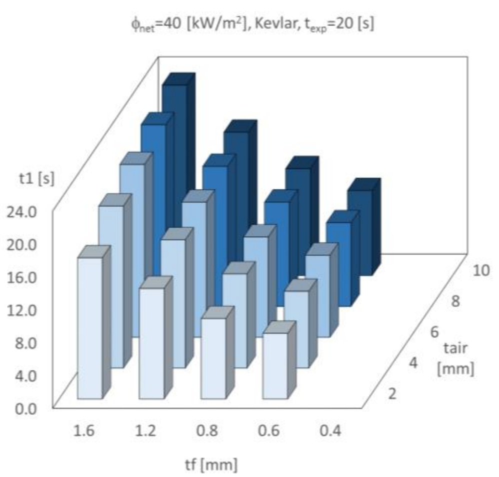
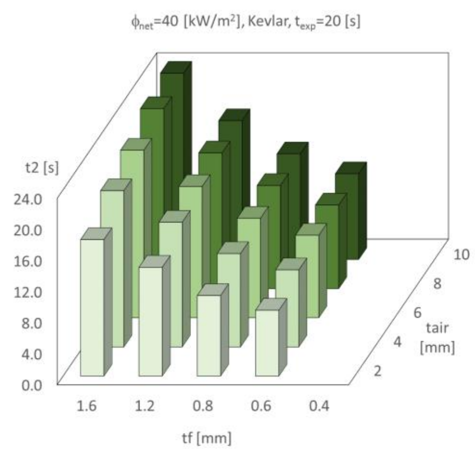
c) 3rd degree burn depending on net heat flux and air gap with $t_{f=}0.4mm$.



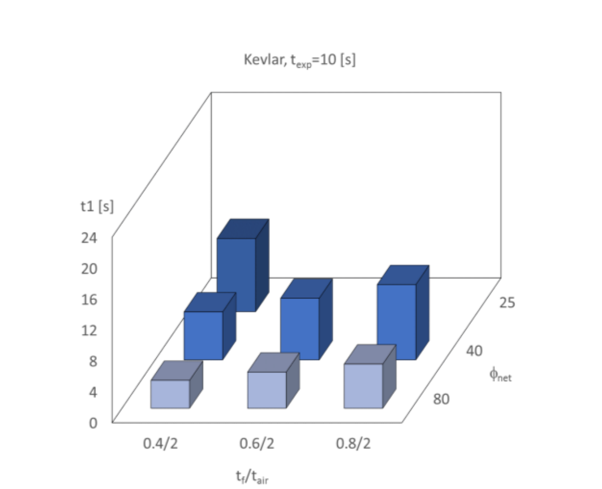
d) 3rd degree burn depending on heat flux and fabric thickness with $t_{air=}2mm$.



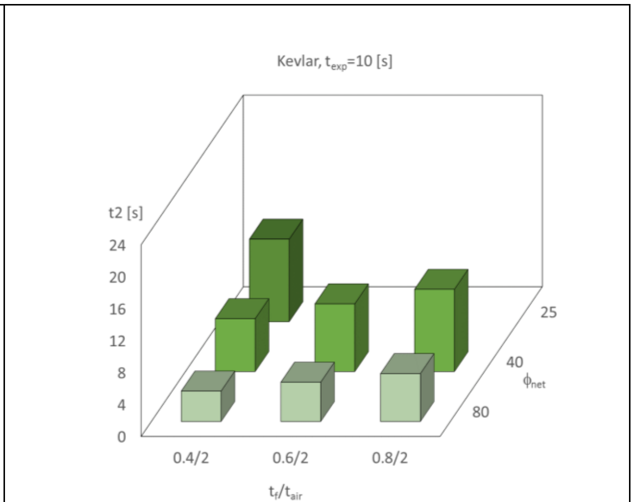


<table>
<tr><td>e) 3rd degree burn depending on heat flux and air gap with $t_{f=}0.6mm$.</td><td>f) 3rd degree burn depending on heat flux and fabric thickness with $t_{air=}2mm$.</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>e) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.</td><td>f) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>g) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.</td><td>h) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.</td></tr>
</table>

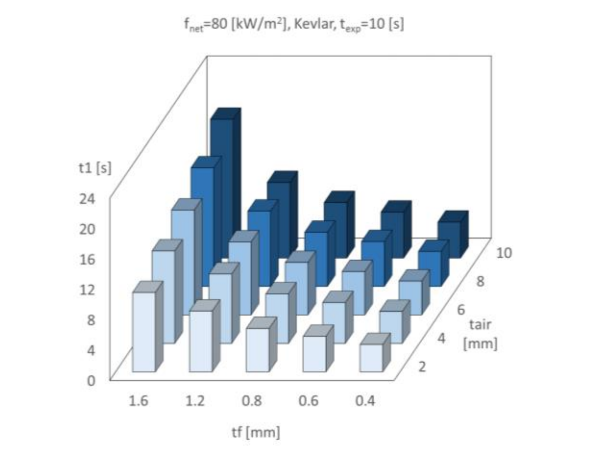
Appendice.2: t1 and t2 results for Kevlar fabric with an exposure time $t_{exp} = 10s$.



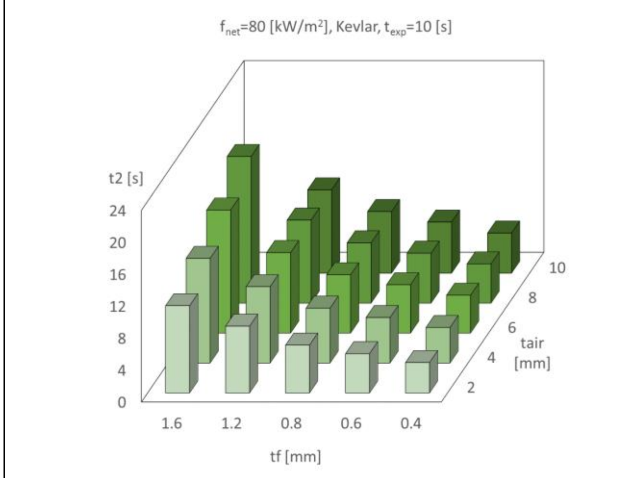
a) 1st degree burn depending on net heat flux.



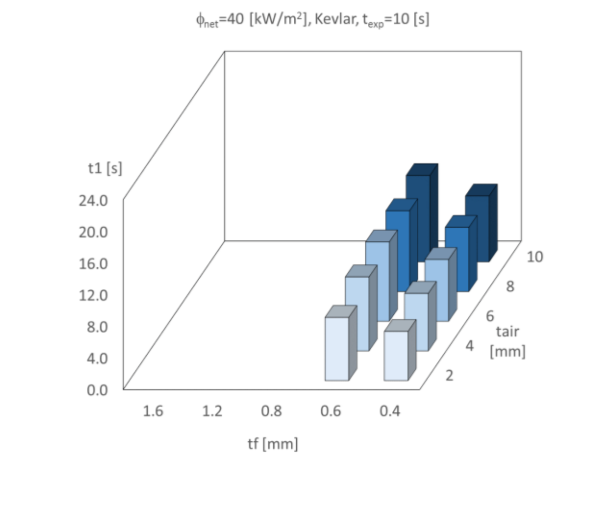
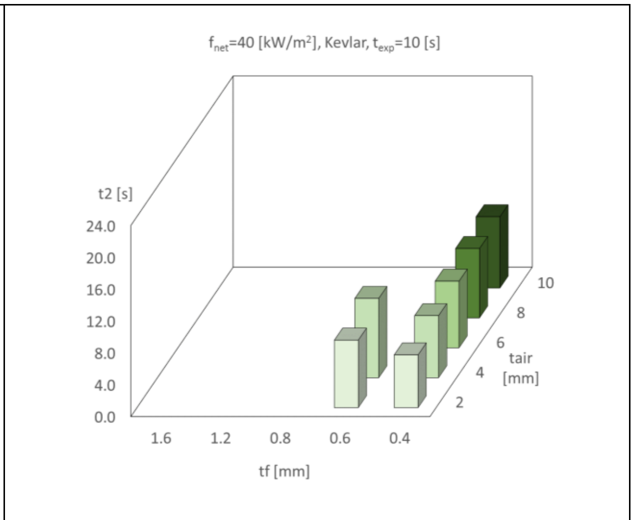
b) 2nd degree burn depending on net heat flux.



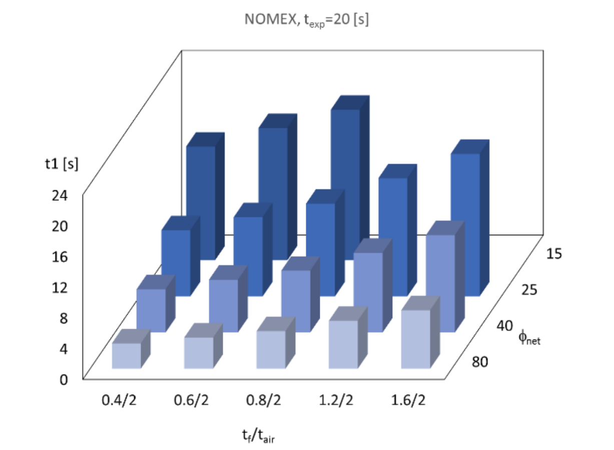
c) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.



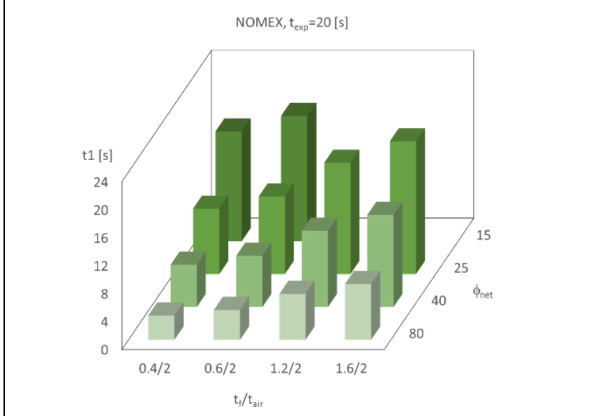
d) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.

	
e) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.	f) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.

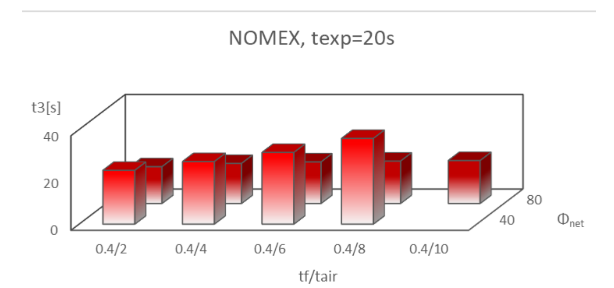
Appendice.3: t1, t2 and t3 results for NOMEX fabric with an exposure time $t_{exp} = 20s$.



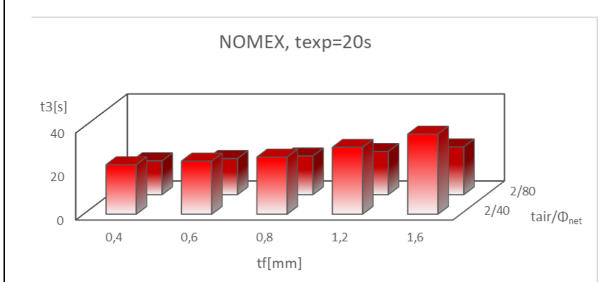
a) 1st degree burn depending on net heat flux.



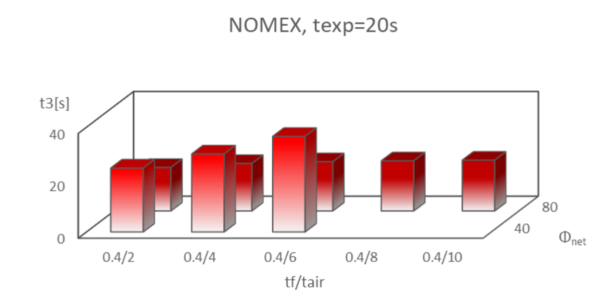
b) 2nd degree burn depending on net heat flux.



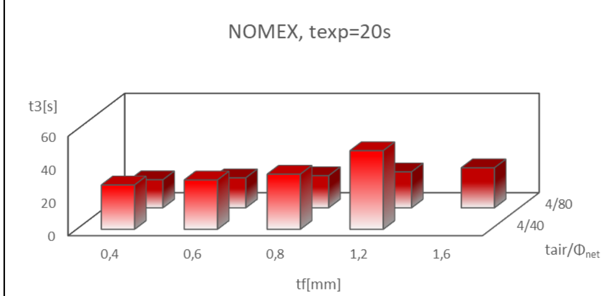
c) 3rd degree burn depending on net heat flux and air gap with $t_{f=}0.4mm$.



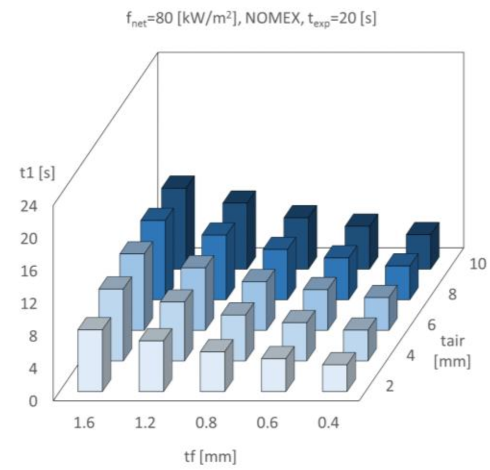
d) 3rd degree burn depending on heat flux and fabric thickness with $t_{air=}2mm$.



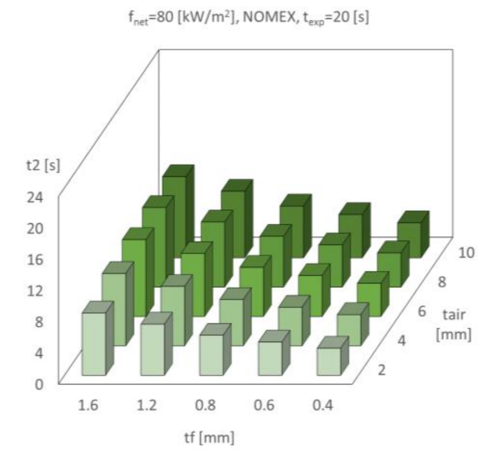
e) 3rd degree burn depending on heat flux and air gap with $t_{f=}0.6mm$.



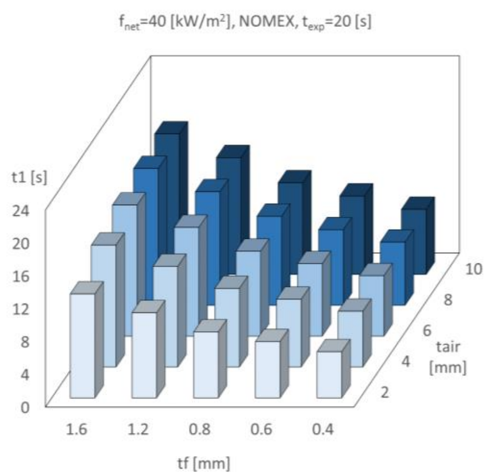
f) 3rd degree burn depending on heat flux and fabric thickness with $t_{air=}2mm$.



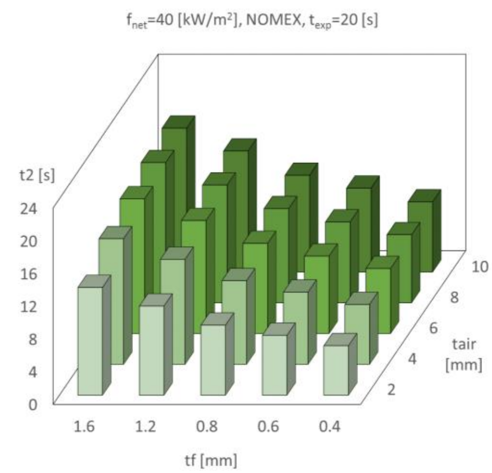
g) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.



h) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.

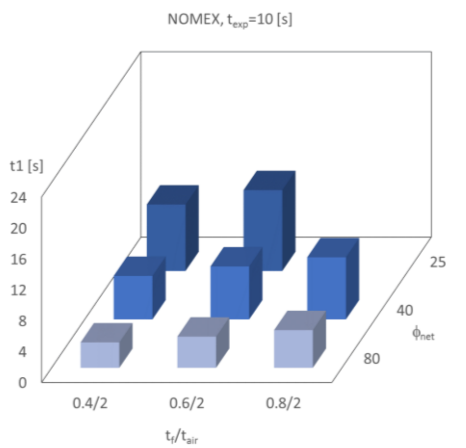


i) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.



j) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.

Appendice.4: t1 and t2 results for NOMEX fabric with an exposure time $t_{exp} = 10s$.

<table>
<tr>
<td>
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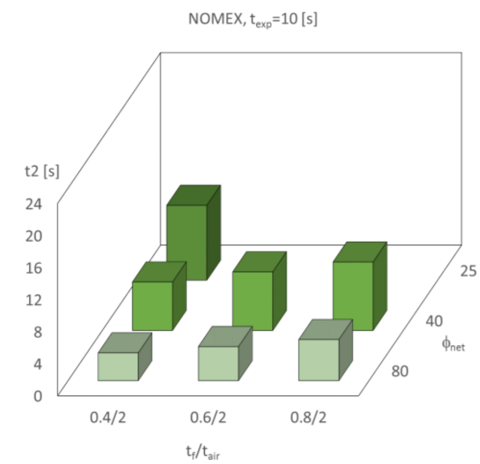
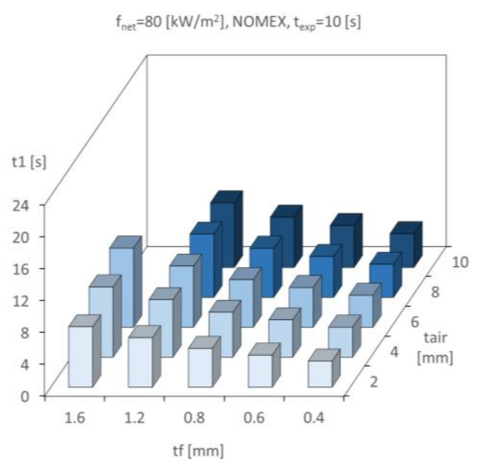
<td>
</td>
</tr>
<tr>
<td>a) 1st degree burn depending on net heat flux.</td>
<td>b) 2nd degree burn depending on net heat flux.</td>
</tr>
<tr>
<td>
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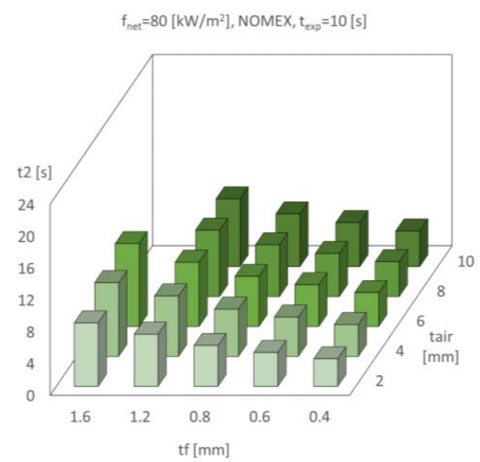
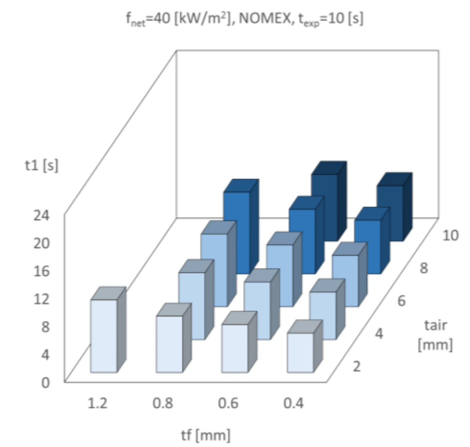
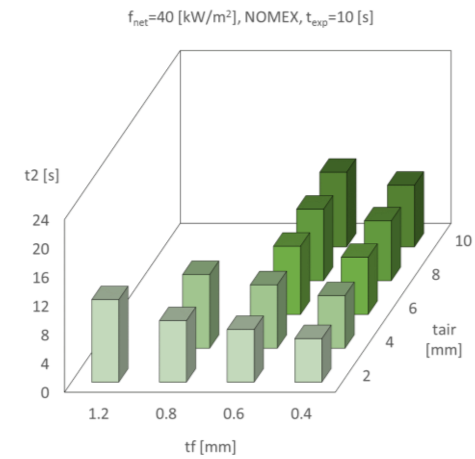
<td>
</td>
</tr>
<tr>
<td>c) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.</td>
<td>d) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 80 kW/m2.</td>
</tr>
</table>

	
e) 1st degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.	f) 2nd degree burn depending on fabric and air thicknesses, for a net heat flux of 40 kW/m2.