HEAT TRANSFER MODEL TO PREDICT SKIN BURN INJURY FOR FIREFIGHTERS

ZAINA NORHALLIS BINTI ZAINOL

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

School of Mechanical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JULY 2021

DEDICATION

This thesis is dedicated to my mother. May Allah grants her a place in Jannah. To my family thank you for supports and sacrifices throughout the PhD journey.

ACKNOWLEDGEMENT

First and foremost, Alhamdulillah, there is no one but Allah who I cannot be indebted and grateful enough for every guidance and blessing that He has showered upon me in the process of completing my thesis. I would like to wish a token of appreciation for the amazing people that I have met during the journey. Also much in hand was my supervisors Assoc. Professor Dr. Masine Md Tap and Assoc. Professor Dr. Haslinda Mohamed Kamar who cared to share upon her knowledge, guidance and motivation. I am also indebted to Ministry of Higher Education (MoHE) and Universiti Teknologi Malaysia (UTM) for funding my PhD study.

Not forgetting in the list are my colleagues in whom I share fears, doubts and happiness throughout the study. I am heartily thankful to my family for giving me the financial support I needed, giving me strength and for always being there for me. I optimistically look forward for this thesis to be an appeal for the younger generation hence makes this as a reference for them.

ABSTRACT

Skin burn injury is common among firefighters despite being encapsulated in the personal protective clothing. However, it is complex to predict skin burn during actual firefighting scenarios due to complex clothing geometries and thermal hazard environment. The objectives of this research were to develop a heat transfer model for predicting skin burn injury for firefighters and identify the causative factors affecting skin burn. A heat transfer model of a multilayer personal protective clothing furnished with human skin was developed using the Finite Element Method. The model considered bioheat equations that includes metabolic heat generation and blood perfusion for predicting skin burn injury. The model employed a quarter cylinder (radial) geometry to represent human limb overlays with Aralite material under wet and dry conditions. The factors such as air gap, heat flux and vapour were considered in skin burn analysis. The validation of the model was carried out by comparing skin temperatures at specified positions based on the published experimental data. The percentage error is less than 17% which is acceptable according to ASHRAE's prescription. The result shows that air gap thickness of 1 mm able to reduce the skin temperature by 10°C and the skin temperature can be reduced further as the air gap thickened. In dry conditions, each 1000 W/m^2 increment of heat flux will increase the skin temperature by 2°C. While, in wet condition, a significant increase of 4°C of the skin temperature was observed for every 1000 W/m^2 increment due the material properties of the personal protective clothing when it was altered and enhanced heat transfer across multiple layers of wet fabric. The presence of vapour under a constant heat flux of 7000 W/m^2 for 25 seconds increases the skin temperature by 10°C. Based on transient heat transfer analysis, it was observed that steam burn injury occurred due to vapour. The research had developed a parametric study based on the three causative factors specifically for Aralite material. The model could benefit designers in producing and improving protective personal clothing for firefighters.

ABSTRAK

Kecederaan kulit terbakar adalah kecederaan biasa dikalangan anggota bomba walaupun mereka telah memakai pakaian peralatan perlindung diri. Namun begitu, sukar untuk meramalkan kecederaan kulit terbakar kerana geometri pakaian yang kompleks dan bahaya tegasan haba di persekitaran. Objektif kajian adalah untuk membangunkan model pemindahan haba bagi meramalkan luka terbakar dikalangan anggota bomba dan mengenalpasti factor yang memberi kesan kepada luka terbakar. Model pemindahan haba terdiri daripada lapisan pakaian pelindung diri dan kulit manusia menggunakan teknik *Finite Element Method.* Kajian ini menggunakan persamaan bio haba untuk menentukan suhu permukaan kulit manusia dengan mengambil kira pengaruh kadar metabolik and kadar aliran darah. Model yang dicadangkan ialah dalam bentuk geometri suku silinder (radial) yang mewakili bentuk tangan dan kaki manusia menggunakan bahan Aralite di bawah keadaan kering dan lembap. Kajian ini disahkan melalui perbandingan hasil kajian model penyelidik yang lain. Nilai ralat kurang dari 17% mematuhi nilai yang ditetapkan oleh ASHREA. Faktor seperti ruang udara, fluks haba dan kelembapan diambilkira dalam analisis kulit terbakar. Keputusan menunjukkan peningkatan ketebalan ruang udara sebanyak 1mm dapat menurunkan suhu permukaan kulit sebanyak 10°C. Suhu permukaan kulit berkurang sekiranya ruang udara semakin tebal. Dalam keadaan kering, kenaikan fluks haba 1000W/m^2 menyebabkan peningkatan suhu permukaan kulit sebanyak 2°C. Manakala dalam lembap setiap kenaikan fluks haba 1000W/m^2 menyebabkan peningkatan 4°C suhu permukaan kulit. Kehadiran wap di bawah fluks haba 7000W/m^2 yang tetap selama 25saat akan meningkatkan suhu sebanyak 10°C. Ini kerana perubahan sifat bahan and peningkatan pemindahan haba melalui lapisan fabrik yang lembap. Berdasarkan analisis pemindahan haba dalam keadaan *transient,* hasil kajian mendapati kehadiran wap menyebabkan berlakunya kejadian luka terbakar akibat stim. Kajian ini telah membangunkan kajian parametrik berdasarkan tiga faktor utama untuk bahan Aralite. Model ini sangat bermanfaat untuk membuat dan memperbaiki rekaan pakaian pelindung diri dikalangan anggota bomba.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

SCBA - Self-Contained Breathing Apparatus
SOP - Standard Operating Procedure
TPP - Thermal Protective Performance
RPP - Radiant Protective Performance
TPI - Thermal Performance Index
HTF - Transmission Factor
RHTI - Radiant Heat Transfer Index
HTI - Heat Transfer Index
SEI - Stored Energy Index
PDE - Partial Differential Equation
CFD - Computational Fluid Dynamic
FEM - Finite Element Method
FDM - Finite Difference Method
GIT - Grid Independent Test
GCI - Grid Convergence Index
FVM - Finite Volume Method
R - Convergence Ratio

LIST OF SYMBOLS

T - Temperature
x - Thickness
$q\dot{m}$ - Metabolic heat generation
$\dot{q}_p$ - Blood profusion heat rates
k - Thermal conductivity
w - Volumetric blood flow
ρ_b - Blood density
c_b - Blood thermal conductivity
T_a - Arterial temperature
L_m - Muscle thickness
L_{sk} - Skin thickness
T_∞ - Surrounding temperature
T_c - Core temperature
T_i - Temperature at between muscle and skin
T_{sk} - Skin temperature
q - Heat transfer rate
R_{tot} - Total thermal resistance
L_{sk} - Skin thickness
k_{sk} - Thermal conductivity of the skin
A - Skin surface area
h_c - Convection heat transfer coefficient
h_r - Radiation heat transfer coefficient
$\theta_{(0)}$ - Excess temperature at boundary
$\theta_{(Lm)}$ - Excess temperature at muscle
θ_c - Excess temperature at core
θ_i - Excess temperature between muscle and skin
θ - Excess temperature
x - thickness
$\tilde{m}$ - Mass flux

$q_{|yx=Lm}$ - Heat transfer leaving the muscle

k_m - Thermal conductivity of the muscle

$q_{cond|x=Lsk}$ - Heat transfer by conduction through the skin layer

q_{rad} - Heat transfer by radiation

q_{conv} - Heat transfer by convection

ρ - Effective density

ε_{bw} - Volume fraction of water absorbed in solid phase

ρ_w - Water density

ε_{ds} - Volume fraction of the dry solid fibre (constant)

ρ_{ds} - density of dry solid

ε_γ - volume fraction in the gas phase

ρ_v - density of water vapour

ρ_a - density of dry air

c_p - effective specific heat

$(c_p)_w$ - specific heat of liquid water

$(c_p)_{ds}$ - specific heat of dry solid

$(c_p)_v$ - specific heat of water vapour

$(c_p)_a$ - specific heat of dry air

k_{eff} - effective thermal conductivity of the fabric

k_σ - thermal conductivity of the solid phase

k_γ - thermal conductivity of the gas phase

k_v - thermal conductivity of the saturated water vapour

k_a - thermal conductivity of the dry air

k_w - thermal conductivity of the liquid water

k_{ds} - thermal conductivity of the dry solid

ρ_g - density of the gaseous phase

$(c_p)_g$ - specific heat of gas phase

ε_l - volume fraction for liquid

ε_b - volume fraction for bound water

ε_f - volume fraction for fibre

ε_g - volume fraction for gas

k_g - thermal conductivity for gas phase

k_s - thermal conductivity for solid phase

k_l - thermal conductivity of the free liquid water

ρ_l - density of the free liquid

ρ_f - density of the dry fibre

k_b - thermal conductivity of the bound water

k_f - thermal conductivity of the fibre

$(c_p)_l$ - specific heat of liquid

$(c_p)_b$ - specific heat of bound water

$(c_p)_f$ - specific heat of fibre

$(c_p)_v$ - specific heat of water vapour

$(c_p)_a$ - specific heat of dry air

F_s - Safety factor

ε - Relative error

r^p - ratio of control volumes in the fine and coarse meshes

N_{fine} - Number of elements for fine mesh

N_{coarse} - Number of elements for coarse mesh

f_1 - Solution of fine mesh

f_2 - Solution of medium mesh

f_3 - Solution of coarse mesh

p - formal order of accuracy of the algorithm

R - Convergence ratio

ε_{21} - Relative error for medium and fine mesh solution

ε_{32} - Relative error for coarse and medium mesh solution

Nu_D - Nusselt number for long horizontal cylinder

Ra_D - Rayleigh number for the long horizontal cylinder

Pr - Prandtl Number

Ra_D - Rayleigh number for the long horizontal cylinder

g - Gravitational acceleration

β - Expansion coefficient

D - Diameter

v - kinematic viscosity

α - thermal diffusivity

h - natural convection coefficient

Nu_D - Nusselt number for long horizontal cylinder

LIST OF APPENDICES

CHAPTER 1

Introduction

1.1 Introduction

This chapter identifies the objectives, problem statement, scopes and the significance of the study. The chapter presents the firefighter’s thermal hazard during work duty. This chapter elaborates briefly the current methodology to evaluate effectiveness of the flame-retardant material and limitations.

1.2 Research Background

The personal protective clothing is worn to protect against thermal hazards. In firefighting, the firefighters are often exposed to extreme heat of radiant, flame, hot gases, steam and explosions. It is very complex to predicts in the firefighting situation because there are factors that need to be considered. In United States, approximately 100 firefighters suffered from critical injuries. There are more than 30000 firefighters subjected to injuries during fire suppression (Karter, 2009). The most common areas suffered from burn injuries is in the head, human limb, neck and shoulder (Karter, 2012). It is found that scalds burns of 65% is one of the common injuries followed by flame burns and the remaining 15% suffered from compression burns (Kahn et al., 2012).

The type of burn degree is classified by the depth of skin injuries. The first degree burns are injuries that only affect the outer layer of the skin surface known as the epidermis. The second degree burn is identified as the wound that penetrates across the dermis. The third degree burn occurs from the epidermis and dermis penetrating through the major third layer of the skin known as the hypodermis (Singer et al., 2014). In order to protect humans against burn injuries, protective clothing is worn. The flame retardant material comprises of the outer shell, moisture barrier and the thermal liner. The outer shell is the outmost layer of the fabric that is directly in contact with the fire. It is made of Aramid fibre named as Nomex (Hamouda, 2005). The second layer of the fabric is moisture barrier that made of light knitted fibre coated with the outer shell. The thermal liner is the third layer of the fabric that avoids heat transfer penetrating through the skin (Lawson et al., 2005). Despite encapsulated by the flame-retardant material, burn injury still occurred in firefighting.

Heat flux transmitted from these thermal hazards in firefighting scenario ranges from 20 – 160 kW/m^2 and usually occurred during extreme fires and explosions (He et al., 2017). Barr et al. (2010) discovered that the tolerance time for the existing protective clothing that can be sustained by a human under heat flux within 5 to 20 seconds only. Heat transfer by radiation is frequently present in all the thermal hazards. Skin burn injuries can occur under low radiation intensity of heat flux ranging from 5 kW/m^2 to 20 kW/m^2 (Barr et al., 2010). The presence of moisture strongly affects burn injury, as water used to suppress fire and sweat profusion is absorbed through the clothing layers. It alters the material thermal conductivity and specific heat capacity enhanced heat transfer to the skin. Skin burn injury is more severe with moisture rather than with dry clothing material (Keiser, 2007; Keiser et al., 2008; Keiser & Rossi, 2008; Keiser et al., 2010). Furthermore, these exposure causes burn injuries are usually taken within minutes of heat exposure (Holmér et al., 2006a).

The prediction of skin burn can be done by using heat transfer analysis with the mathematical model and experimentation. Both are designed to represent the human skin but predicting the burn injury is extremely difficult because there are many factors affecting burn injuries. However, the prediction of skin temperature can be done if human skin material properties and its material properties are known. Previous researchers utilized bench scale test (G. W. Song et al., 2011) and thermal manikin (Bröde et al., 2008; Ming Fu et al., 2015; Havenith et al., 2006; Havenith et al., 2005; Qian & Fan, 2006; Sun & Fan, 2017). These are done using a specimen of flame-retardant material under continuous fire to determine the skin temperature. Current experimentation is inaccurate as it does not consider the heat gained from metabolic heat to the surrounding skin tissue. However, it is unsafe to use human subject in experimentation. Therefore, this research will adapt mathematical model from Pennes (1948) bioheat equation in predicting human skin temperature with the blood perfusion and the metabolic heat generations.

Moisture significantly affects the protective clothing thermal protection. According to Keiser and Rossi (2008) steam burn injury occur in wet condition under continuous heat exposure. This causes enhancement of heat transfer across the multilayers fabric developing evaporation and vaporization of moisture. Firefighting requires spraying of water on flame to control fire. This form external source of moisture. While internal moisture source comes from sweating (Keiser & Rossi, 2008).

In this research, a new approach is developed to predict burn injury of personal protective clothing in wet and dry material condition by using the bioheat equation and finite element analysis.

1.3 Problem Statement

The current method of predicting skin burn injury is done by using experimental method such as bench scale test, thermal manikin test and test method for wet sample. These methods produce unreliable outcome as they do not represent the behaviour of human skin.

The human skin temperature is not constant. It is affected by blood perfusion, human activities and surroundings conditions. The blood perfusion is influenced by the clothing type and wetness. Human activities are affected by the metabolic rate. The surrounding conditions such as the combination of moisture and heat can cause steam burn injury. Therefore, a model that can predict the human skin temperature without using the human experimentation need to be developed.

There are a number of researchers who developed mathematical model to predict burn injury using one dimensional plane geometry. However, this geometry is not representative of the human limbs because it consists of cylindrical geometry where the heat transfer is in radial direction. Thus, a quarter cylindrical geometry model has to be developed for a reliable representation of the human limbs in order to predict skin burn.

1.4 Research Question

The research questions are as follow:

(a) How to predict firefighter’s skin burn injury?

(b) What are the causative factors affecting skin burn?

(c) How will moisture in flame retardant material affect skin burn injury ?

1.5 Research Objectives

The objectives of the study are to:

(a) Develop heat transfer model for predicting skin burn injury.

(b) Determine the causative factors affecting skin burn.

(c) Develop a parametric study for Aralite material.

1.6 Research Scope

The scopes of the research are as follow:

(d) The heat transfer model developed will be based on the Aralite material under sedentary position.

(e) The causative factors affecting skin burn that will be studied are the air gap thickness, heat flux and moisture.

(f) The parametric study of the Aralite material is under wet and dry conditions.

1.7 The Significance of the Research

The proposed model can predict burn injury with consideration of blood perfusion and metabolic heat generation by using Pennes bioheat equation. This is a better representation of the human skin. The proposed model can replace exhaustive experimentation.

The proposed model enables the study of the combined effect of moisture, air gap thickness and the heat flux. These are the most significant factors that influenced the formation of the skin burn injury. Furthermore, it can predict the occurrence of steam burn injury under moisture of wet condition.

Previously researchers have used numerical method to predict firefighter's skin temperature, but they only considered one dimensional plane geometry. However, the proposed model is in one dimensional quarter cylinder (radial) geometry that better represents the human limb and produce reliable outcome in predicting the skin temperature.

The proposed model can be a tool to assess the effectiveness of the protective clothing specifically Aralite material. The model provides systematic procedure and method to assess thermal performance of the flame-retardant material. The proposed model can simulate the thermal hazards that caused skin burns under wet and dry conditions. This can provide understandings of heat transfer mechanisms across the fabric in preventing occurrence of burn injury during firefighting.

1.8 The Outline of the Thesis

Chapter 1 is the introductory of the study to comprehend the thermal hazards of firefighters. It elaborates the methods used to evaluates the flame-retardant material and its limitations. The chapter presented problem statement, research objective and the importance of the research.

Chapter 2 is the literature review of the study. It discusses the material and structure of the protective garments. The significant factors that have effects on skin burn injury are identified based on findings of past researchers. The current methods and limitations that are used to predict skin burn is emphasized.

Chapter 3 presents the methods of the research in chronological order. The materials and procedure in determining skin burn are also presented in this chapter.

Chapter 4 discusses the development of the proposed model in determining the firefighter's skin burn under wet and dry conditions. This chapter presents the equation applied in the model. It also shows the development of finite element model. Verification and validation are developed to ensure the model is reliable in predicting skin burn.

Chapter 5 discusses the result of the study. The findings from the proposed model is presented in this chapter. The significant effect of air gap, heat flux and moisture are emphasized in this chapter.

Chapter 6 discusses factors affecting skin burn injury. It discusses the significant factors affecting skin burn. The threshold of predicted pain, first degree burn and second degree burn in body parts are presented in this chapter.

Chapter 7 presents the conclusion of the study. It summarizes the overall important outcomes of this research. It also presents the recommendations for future work.

(e) Expand wet material database

Currently the gas and liquid absorbed in the clothing material is specifically for Aralite material provided by Chitrphiromsri (2005). There are many materials for personal protective clothing available in the market such as combination of Meta-aramid, Polytetraflouroethylene, Nomex and Kevlar (Lawson et al., 2010). However, there is a lack of data on their porosity and absorption characteristics. During firefighting, sweat is produce excessively due to strenuous physical activities (Holmér et al., 2006b). The amount of sweat, liquid and gas absorbed in the material differ depending on the materials porosity. Therefore, it is crucial to conduct further experiment to have more information on the amount bound water, liquid and gas due to the evaporation process for these materials. The amount of bound water, liquid and gas will affect the material properties, thermal performance and tolerance time to burn injury. Therefore, there is a need to expand the thermal protective clothing performance database in wet condition. This will provide a proper guidance for users and the thermal protective clothing designers to provide better protection against heat and fire.

(f) Compression condition

Compression condition of the multilayer's fabric is a significant factor to be considered in the evaluation tool of the personal protective clothing. The compression normally occurs due to human body movement such as crawling and kneeling motion resulting in skin burn. The results show that the skin burn occur faster without air gap. The air gap do not appear if the fabric is compressed and there may be reduction in the amount of moisture absorbed in the fabric. Compression decreases fabric thickness and air gap hence the heat transfer rate will rise and reduces threshold for burn injury. Therefore, there is a necessity to study compression effect to the skin burn injury.

REFERENCES

ANSYS. (2013). ANSYS Fluent User's Guide A. Southpointe. http://www.pmt.usp.br/academic/martoran/notasmodelosgrad/ANSYS%20Fluent%20Users%20Guide.pdf

Ashley, C. D., Luecke, C. L., Schwartz, S. S., Islam, M. Z., & Bernard, T. E. (2008). Heat strain at the critical WBGT and the effects of gender, clothing and metabolic rate. International Journal of Industrial Ergonomics, 38(7-8), 640-644. https://doi.org/10.1016/j.ergon.2008.01.017

ASHRAE. (2001). Handbook Fundamentals. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 111.

ASTM International. (2008). Standard test method for unsteady-state heat transfer evaluation of flame resistant materials for clothing with burn injury prediction. (F2703 - 08). https://www.astm.org/Standards/F2703.htm

ASTM International. (2011). Test Method for Measuring the Transmitted and Stored Energy of Firefighter Protective Clothing Systems. (ASTM F2731 - 18). https://www.astm.org/Standards/F2731.htm

ASTM International. (2013). Test Method for Unsteady-State Heat Transfer Evaluation of Flame Resistant Materials for Clothing with Burn Injury Prediction. (F2703-08(2013)). https://www.astm.org/Standards/F2700.htm

ASTM International. (2015). Standard test method for radiant heat resistance of flame resistant clothing materials with continuous heating. (F1939 - 2015). https://www.astm.org/Standards/F1939.htm

Bakri, I., Lee, J.-Y., Nakao, K., Wakabayashi, H., & Tochihara, Y. (2012). Effects of firefighters' self-contained breathing apparatus' weight and its harness design on the physiological and subjective responses. Ergonomics, 55(7), 782-791. https://doi.org/10.1080/00140139.2012.663506

Barker, R. L. (2005). A Review of gaps and limitations in test methods for first responder protective clothing and equipment: a final report presented to National Personal Protection Technology Laboratory, National Institute for Occupational Safety and Health (NIOSH).

Barker, R. L., Guerth-Schacher, C., Grimes, R., & Hamouda, H. (2006). Effects of moisture on the thermal protective performance of firefighter protective clothing in low-level radiant heat exposures. Textile Research Journal, 76(1), 27-31. https://doi.org/10.1177/0040517506053947

Barr, D., Gregson, W., & Reilly, T. (2010). The thermal ergonomics of firefighting reviewed. Appl Ergon, 41(1), 161-172. https://doi.org/10.1016/j.apergo.2009.07.001

Bernard, T. E., & Ashley, C. D. (2009). Short-term heat stress exposure limits based on wet bulb globe temperature adjusted for clothing and metabolic rate. Journal of occupational and environmental hygiene, 6(10), 632-638. https://doi.org/10.1080/15459620903133642

Bernard, T. E., Caravello, V., Schwartz, S. W., & Ashley, C. D. (2007). WBGT clothing adjustment factors for four clothing ensembles and the effects of metabolic demands. Journal of occupational and environmental hygiene, 5(1), 1-5. https://doi.org/10.1080/15459620701732355

Britton, C., Lynch, C. F., Ramirez, M., Torner, J., Buresh, C., & Peek-Asa, C. (2013). Epidemiology of injuries to wildland firefighters. The American journal of emergency medicine, 31(2), 339-345. https://doi.org/10.1016/j.ajem.2012.08.032

Bröde, P., Havenith, G., Wang, X., Candas, V., Den Hartog, E. A., Griefahn, B., Holmér, I., Kuklane, K., Meinander, H., & Nocker, W. (2008). Non-evaporative effects of a wet mid layer on heat transfer through protective clothing. European journal of applied physiology, 104(2), 341-349. https://doi.org/10.1007/s00421-007-0629-y

Bröde, P., Kuklane, K., Candas, V., Den Hartog, E. A., Griefahn, B., Holmér, I., Meinander, H., Nocker, W., Richards, M., & Havenith, G. (2010). Heat gain from thermal radiation through protective clothing with different insulation, reflectivity and vapour permeability. International Journal of Occupational Safety and Ergonomics, 16(2), 231-244.

Cai, G., Xu, Z., Li, W., & Yu, W. (2015). Experimental investigation on the thermal protective performance of nonwoven fabrics made of high-performance fibers. Journal of Thermal Analysis and Calorimetry, 121(2), 627-632. https://doi.org/10.1007/s10973-015-4698-6

Campbell, R. (2018). US Firefighter Injuries on the Fireground, 2010-2014. Fire technology, 54(2), 461-477. https://doi.org/10.1007/s10694-017-0692-9

Cheung, S., Petersen, S., & McLellan, T. (2010). Physiological strain and countermeasures with firefighting. Scandinavian journal of medicine & science in sports, 20, 103-116. https://doi.org/10.1111/j.1600-0838.2010.01215.x

Chitrphiromsri, P. (2005). Modeling of Thermal Performance of Firefighter Protective Clothing during the Intense Heat Exposure (PhD Dissertations). http://www.lib.ncsu.edu/resolver/1840.16/4307

Chitrphiromsri, P., & Kuznetsov, A. (2005). Modeling heat and moisture transport in firefighter protective clothing during flash fire exposure. Heat and mass transfer, 41(3), 206-215. https://doi.org/10.1007/s00231-004-0504-x

Chitrphiromsri, P., Kuznetsov, A., Song, G., & Barker, R. (2006). Investigation of feasibility of developing intelligent firefighter-protective garments based on the utilization of a water-injection system. Numerical Heat Transfer, Part A: Applications, 49(5), 427-450.

Cooper, T., & Trezek, G. (1971). Correlation of thermal properties of some human tissue with water content. Aerospace medicine, 42(1), 24-27.

Cuddy, J. S., & Ruby, B. C. (2011). High work output combined with high ambient temperatures caused heat exhaustion in a wildland firefighter despite high fluid intake. Wilderness & environmental medicine, 22(2), 122-125. https://doi.org/10.1016/j.wem.2011.01.008

Dan, D., Tian, T., Guowen, S., & McDonald, A. (2010). Characterizing the performance of a single-layer fabric system through a heat and mass transfer model - Part I: Heat and mass transfer model. Textile Research Journal, 81(4), 398-411. https://doi.org/10.1177/0040517510388547

Den Hartog, E. A., & Havenith, G. (2010). Analytical study of the heat loss attenuation by clothing on thermal manikins under radiative heat loads. International Journal of Occupational Safety and Ergonomics, 16(2), 245-261.

Deng, M., Wang, Y., & Li, P. (2018). Effect of air gaps characteristics on thermal protective performance of firefighters’ clothing: A review. International Journal of Clothing Science and Technology, 30(2), 246-267.

Elgafy, A., & Mishra, S. (2014). A heat transfer model for incorporating carbon foam fabrics in firefighter's garment. Heat and mass transfer, 50(4), 545-557. https://doi.org/10.1007/s00231-013-1259-z

Evers, L. H., Bhavsar, D., & Mailänder, P. (2010). The biology of burn injury. Experimental Dermatology, 19(9), 777-783. https://doi.org/10.1111/j.1600-0625.2010.01105.x

Ferreira, M., & Yanagihara, J. I. (2009). A transient three-dimensional heat transfer model of the human body. International Communications in Heat and Mass Transfer, 36(7), 718-724.

Ferreira, M., & Yanagihara, J. I. (2012). A heat transfer model of the human upper limbs. International Communications in Heat and Mass Transfer, 39(2), 196-203. https://doi.org/10.1016/j.icheatmasstransfer.2011.12.004

Fiala, D., Havenith, G., Bröde, P., Kampmann, B., & Jendritzky, G. (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation. International journal of biometeorology, 56(3), 429-441.

Fontana, P., Saiani, F., Grütter, M., Croset, J.-P., Capt, A., Camenzind, M., Morrissey, M., Rossi, R. M., & Annaheim, S. (2017). Exercise intensity dependent relevance of protective textile properties for human thermo-physiology. Textile Research Journal, 87(12), 1425-1434. https://doi.org/10.1177/0040517516654105

Frackiewicz-Kaczmarek, J., Psikuta, A., Bueno, M.-A., & Rossi, R. M. (2015). Air gap thickness and contact area in undershirts with various moisture contents: influence of garment fit, fabric structure and fiber composition. Textile Research Journal, 85(20), 2196-2207.

Fu, M., Chen, W. W., Weng, W. G., Yuan, M. Q., Luo, N., & Xu, X. Y. (2018). Prediction of thermal skin burn based on the combined mathematical model of the skin and clothing. Journal of the Textile Institute, 109(12), 1606-1612. https://doi.org/10.1080/00405000.2018.1437112

Fu, M., Weng, W., & Yuan, H. (2014a). Effects of multiple air gaps on the thermal performance of firefighter protective clothing under low-level heat exposure. Textile Research Journal, 84(9), 968-978.

Fu, M., Weng, W., & Yuan, H. (2014b). Numerical simulation of the effects of blood perfusion, water diffusion, and vaporization on the skin temperature and burn injuries. Numerical Heat Transfer, Part A: Applications, 65(12), 1187-1203.

Fu, M., Weng, W., & Yuan, H. (2014). Quantitative assessment of the relationship between radiant heat exposure and protective performance of multilayer thermal protective clothing during dry and wet conditions. Journal of hazardous materials, 276, 383-392.

Fu, M., Weng, W., & Yuan, H. (2015). Combined effects of moisture and radiation on thermal performance of protective clothing: experiments by a sweating manikin exposed to low level radiation. International Journal of Clothing Science and Technology, 27(6), 818-834. https://doi.org/10.1108/IJCST-05-2014-0064

Fu, M., Yuan, M. Q., & Weng, W. G. (2015). Modeling of heat and moisture transfer within firefighter protective clothing with the moisture absorption of thermal radiation. International Journal of Thermal Sciences, 96, 201-210, Article 4443. https://doi.org/10.1016/j.ijthermalsci.2015.05.008

Gan, Y., Cheng, L., Ding, X., & Pan, N. (2010). Blood flow fluctuation underneath human forearm skin caused by local thermal stimuli of different fabrics.

Journal of Thermal Biology, 35(7), 372-377. https://doi.org/10.1016/j.jtherbio.2010.07.007

Ghaddar, N., Ghali, K., Harathani, J., & Jaroudi, E. (2005). Ventilation rates of micro-climate air annulus of the clothing-skin system under periodic motion. International Journal of Heat and Mass Transfer, 48(15), 3151-3166. https://doi.org/10.1016/j.ijheatmasstransfer.2005.03.00

Ghaddar, N., Ghali, K., & Jones, B. (2003). Integrated human-clothing system model for estimating the effect of walking on clothing insulation. International Journal of Thermal Sciences, 42(6), 605-619. https://doi.org/10.1016/S1290-0729(03)00026-7

Ghali, K., Ghaddar, N., & Jones, B. (2002). Modeling of heat and moisture transport by periodic ventilation of thin cotton fibrous media. International Journal of Heat and Mass Transfer, 45(18), 3703-3714. https://doi.org/ 10.1016/S0017-9310(02)00088-1

Ghali, K., Othmani, M., Jreije, B., & Ghaddar, N. (2009). Simplified heat transport model of a wind-permeable clothed cylinder subject to swinging motion. Textile Research Journal, 79(11), 1043-1055. https://doi.org/https://doi-org.ezproxy.utm.my/10.1177%2F0040517508101460

Ghazy, A. (2017). The Thermal Protective Performance of Firefighters' Clothing: The Air Gap Between the Clothing and the Body [Article]. Heat Transfer Engineering, 38(10), 975-986. https://doi.org/10.1080/01457632.2016.1212583

Ghazy, A., & Bergstrom, D. J. (2010). Numerical Simulation of Transient Heat Transfer in a Protective Clothing System during a Flash Fire Exposure. Numerical Heat Transfer Part a-Applications, 58(9), 702-724, Article Pii 929796171. https://doi.org/10.1080/10407782.2010.516691

Ghazy, A., & Bergstrom, D. J. (2011). Influence of the air gap between protective clothing and skin on clothing performance during flash fire exposure [Article]. Heat and Mass Transfer/Waerme- und Stoffuebertragung, 47(10), 1275-1288. https://doi.org/10.1007/s00231-011-0791-y

Ghazy, A., & Bergstrom, D. J. (2012). NUMERICAL SIMULATION OF HEAT TRANSFER IN FIREFIGHTERS' PROTECTIVE CLOTHING WITH MULTIPLE AIR GAPS DURING FLASH FIRE EXPOSURE. Numerical Heat Transfer Part a-Applications, 61(8), 569-593. https://doi.org/10.1080/10407782.2012.666932

Gibson, P. (1996). Multiphase heat and mass transfer through hygroscopic porous media with applications to clothing materials (Technical Report Natick/TR-97/005, US Army Natick Research, Development and ENgineering Center, Issue.

Guo, Y., Li, Y., Tokura, H., Wong, T., Chung, J., Wong, A. S., Indulal Gohel, M. D., & Hang Mei Leung, P. (2008). Impact of fabric moisture transport properties on physiological responses when wearing protective clothing. Textile Research Journal, 78(12), 1057-1069. https://doi.org/10.1177/0040517508090496

Hamouda, H. (2005). Thermal protective clothing. In Handbook of Environmental Degradation of Materials (pp. 261-275). Elsevier.

Havenith, G., HolmÈr, I., Meinander, H., denHartog, E., Richards, M., Brˆde, P., & Candas, V. (2006). Assessment of thermal properties of of protective clothing and their use. EU Final Report.

Havenith, G., Wang, X., den Hartog, E. A., Griefahn, B., Holmer, I., Meinander, H., & Richards, M. (2005). Interaction effects of radiation and convection measured by a thermal manikin wearing protective clothing with different radiant properties.

He, J., Park, E., Li, J., & Kim, E. (2017). Physiological and psychological responses while wearing firefighters’ protective clothing under various ambient conditions. Textile Research Journal, 87(8), 929-944.

Henriques, F. C., & Moritz, A. R. (1947). Studies of Thermal Injury: I. The Conduction of Heat to and through Skin and the Temperatures Attained Therein. A Theoretical and an Experimental Investigation. The American journal of pathology, 23(4), 530-549. https://www.ncbi.nlm.nih.gov/pubmed/19970945

Holmer, I., & Gavhed, D. (2007). Classification of metabolic and respiratory demands in fire fighting activity with extreme workloads. Appl Ergon, 38(1), 45-52. https://doi.org/10.1016/j.apergo.2006.01.00

Holmér, I., Kuklane, K., & Gao, C. (2006a). Test of firefighter’s turnout gear in hot and humid air exposure. International Journal of Occupational Safety and Ergonomics, 12(3), 297-305. https://doi.org/10.1080/10803548.2006.11076689

Holmér, I., Kuklane, K., & Gao, C. (2006b). Thermal stress on firefighters in extreme heat exposure. 3rd European Conference on Protective Clothing and NOKOBETEF 8. Protective clothing-towards balanced protection,

Huang, D. M., Yang, H., Qi, Z. K., Xu, L., Cheng, X. D., Li, L. M., & Zhang, H. P. (2012). Questionnaire on Firefighters' Protective Clothing in China. Fire technology, 48(2), 255-268. https://doi.org/10.1007/s10694-011-0214-0

Huizenga, C., Zhang, H., Arens, E., & Wang, D. (2004). Skin and core temperature response to partial-and whole-body heating and cooling. Journal of Thermal Biology, 29(7-8), 549-558. https://doi.org/10.1016/j.jtherbio.2004.08.024

Hummel, A., Barker, R., Lyons, K., Deaton, A. S., & Morton-Aslanis, J. (2011). Development of instrumented manikin hands for characterizing the thermal protective performance of gloves in flash fire exposures. Fire technology, 47(3), 615-629. https://doi.org/10.1007/s10694-010-0190-9

Hurnik, M., Blaszczok, M., & Popiolek, Z. (2015). Air distribution measurement in a room with a sidewall jet: a 3D benchmark test for CFD validation. Building and Environment, 93, 319-330.

Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). Fundamentals of heat and mass transfer (6th ed.). John Wiley & Sons.

International Organization for Standardization. (2002a). Protective clothing-protection against heat and fire——Method of test: Evaluation of materials and material assemblies when exposed to a source of radiant heat. (ISO 6942:2002). https://www.iso.org/standard/26327.html

International Organization for Standardization. (2002b). Protective clothing—protection against heat and fire—method of test: evaluation of materials and material assemblies when exposed to a source of radiant heat. (ISO6942:2002). https://www.iso.org/standard/26327.html

International Organization for Standardization. (2003). Clothing for protection against heat and flame—determination of heat transmission on exposure to both flame and radiant heat. (ISO 17492:2003). https://www.iso.org/standard/30698.html

International Organization for Standardization. (2008). Protective clothing against heat and flame: test method for complete garments—prediction of burn injury using an instrumented manikin. (IS0 13506:2008). https://www.iso.org/standard/41154.html

Jaskille, A. D., Ramella-Roman, J. C., Shupp, J. W., Jordan, M. H., & Jeng, J. C. (2010). Critical Review of Burn Depth Assessment Techniques: Part II. Review of Laser Doppler Technology. Journal of burn care & research, 31(1), 151-157. https://doi.org/10.1097/BCR.0b013e3181c7ed60

Jiang, Y. Y., Yanai, E., Nishimura, K., Zhang, H., Abe, N., Shinohara, M., & Wakatsuki, K. (2010). An integrated numerical simulator for thermal performance assessments of firefighters' protective clothing. Fire Safety Journal, 45(5), 314-326. https://doi.org/10.1016/j.firesaf.2010.06.003

Jin, L., Cao, M. L., Yu, W., Hu, J. Y., Yoon, K. J., Park, P. K., & Li, Y. (2018). New approaches to evaluate the performance of firefighter protective clothing materials. Fire technology, 54(5), 1283-1307. https://doi.org/10.1007/s10694-018-0730-2

Kahn, S. A., Patel, J. H., Lentz, C. W., & Bell, D. E. (2012). Firefighter burn injuries: predictable patterns influenced by turnout gear. Journal of burn care & research, 33(1), 152-156.

Karter, M. J. (2009). Patterns of firefighter fireground injuries (National Fire Protection Association Quincy, MA, Issue. http://tkolb.net/FireReports/FiregroundInjuries03-06.pdf

Karter, M. J. (2011). Fire loss in the United States during 2010. National Fire Protection Association Quincy, MA. https://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2011/September-October-2011/Features/Fire-Loss-in-the-United-States-During-2010

Karter, M. J. (2012). Patterns of firefighter fireground injuries. National Fire Protection Association Quincy, MA.

Keiser, C. (2007). Steam Burns: moisture management in firefighter protective clothing ETH Zurich]. https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/4133/1/eth-29868-01.pdf

Keiser, C., Becker, C., & Rossi, R. M. (2008). Moisture transport and absorption in multilayer protective clothing fabrics. Textile Research Journal, 78(7), 604-613. https://doi.org/10.1177/0040517507081309

Keiser, C., & Rossi, R. M. (2008). Temperature analysis for the prediction of steam formation and transfer in multilayer thermal protective clothing at low level thermal radiation. Textile Research Journal, 78(11), 1025-1035. https://doi.org/10.1177/0040517508090484

Keiser, C., Wyss, P., & Rossi, R. M. (2010). Analysis of steam formation and migration in firefighters’ protective clothing using X-ray radiography. International Journal of Occupational Safety and Ergonomics, 16(2), 217-229. https://doi.org/ 10.1080/10803548.2010.11076839

Kenefick, R. W., Cheuvront, S. N., & Sawka, M. N. (2007). Thermoregulatory function during the marathon. Sports medicine, 37(4-5), 312-315. https://doi.org/10.2165/00007256-200737040-00010

Kilinc, F. S. (2013). Handbook of fire resistant textiles. Elsevier.

Kim, J.-H., Powell, J. B., Roberge, R. J., Shepherd, A., & Coca, A. (2014). Evaluation of protective ensemble thermal characteristics through sweating hot plate, sweating thermal manikin, and human tests. Journal of occupational and environmental hygiene, 11(4), 259-267. https://doi.org/10.1080/15459624.2013.858820

Kothari, V., & Chakraborty, S. (2016). Protective performance of thermal protective clothing assemblies exposed to different radiant heat fluxes. Fibers and Polymers, 17(5), 809-814.

Kwaśniewski, L. (2013). Application of grid convergence index in FE computation. Bulletin of the Polish Academy of Sciences: Technical Sciences, 61(1), 123-128.

Lamb, G. E. (1992). Heat and water vapor transport in fabrics under ventilated conditions. Textile Research Journal, 62(7), 387-392. https://doi.org/10.1177/004051759206200704

Lapka, P., Furmanski, P., & Wisniewski, T. (2017). Assessment of thermal performance of protective garments: The advanced numerical model. International Journal of Numerical Methods for Heat & Fluid Flow, 27(5), 1078-1097. https://doi.org/10.1108/HFF-03-2016-0101

Lapka, P., Furmański, P., & Wisniewski, T. S. (2016). Numerical modelling of transient heat and moisture transport in protective clothing. Journal of Physics: Conference Series,

Lawson, J. R., Mell, W. E., & Prasad, K. (2010). A Heat Transfer Model for Firefighters' Protective Clothing, Continued Developments in Protective Clothing Modeling. Fire technology, 46(4), 833-841. https://doi.org/10.1007/s10694-010-0139-z

Lawson, J. R., Walton, W. D., Bryner, N. P., & Amon, F. K. (2005). Estimates of Thermal Properties for Fire Fighters' Protective Clothing Materials. US Department of Commerce, National Institute of Standards and Technology.

Lawson, L. K., Crown, E. M., Ackerman, M. Y., & Douglas Dale, J. (2004). Moisture effects in heat transfer through clothing systems for wildland firefighters. International Journal of Occupational Safety and Ergonomics, 10(3), 227-238.

Lee, S., Park, C., Kulkarni, D., Tamanna, S., & Knox, T. (2010). Heat and mass transfer in a permeable fabric system under hot air jet impingement. 2010 14th International Heat Transfer Conference,

Lei, Z., Qian, X., & Zhang, X. (2018). Assessment of thermal protective performance of firefighter's clothing by a sweating manikin in low-level radiation. International Journal of Clothing Science and Technology, 31(1), 145-154. https://doi.org/https://doi.org/10.1108/IJCST-04-2018-0061

Li, J., Lu, Y., & Li, X. (2012). Effect of relative humidity coupled with air gap on heat transfer of flame-resistant fabrics exposed to flash fires. Textile Research Journal, 82(12), 1235-1243. https://doi.org/ 10.1177/0040517512436830

Li, J., Zhang, Z., & Wang, Y. (2013). The relationship between air gap sizes and clothing heat transfer performance. The Journal of The Textile Institute, 104(12), 1327-1336. https://doi.org/ 10.1080/00405000.2013.802080

Li, X.-h., Lu, Y.-h., Li, J., Wang, Y.-y., & Zhou, L. (2012). A new approach to evaluate the effect of moisture on heat transfer of thermal protective clothing under flashover. Fibers and Polymers, 13(4), 549-554. https://doi.org/10.1007/s12221-012-0549-2

Ljubičić, A., Varnai, V. M., Petrinec, B., & Macan, J. (2014). Response to thermal and physical strain during flashover training in Croatian firefighters. Appl Ergon, 45(3), 544-549. https://doi.org/10.1016/j.apergo.2013.07.011

Mell, W. E., & Lawson, J. R. (2000). A heat transfer model for firefighters' protective clothing. Fire technology, 36(1), 39-68.

Mercer, G., & Sidhu, H. (2008). Mathematical modelling of the effect of fire exposure on a new type of protective clothing. ANZIAM Journal, 49, 289-305.

Morel, Bedek, G., Salaün, F., & Dupont, D. (2014). A review of heat transfer phenomena and the impact of moisture on firefighters' clothing and protection. Ergonomics, 57(7), 1078-1089. https://doi.org/10.1080/00140139.2014.907447

Mukaddes, A. M. M., Jaher, M. R., Roy, D., & Shioya, R. (2018). A Simulation Study of Bio-heat Transfer in Human Skin under Different Burning Conditions. In M. AlNur, S. R. Ahmed, & M. Ali (Eds.), Proceedings of the 12th International Conference on Mechanical Engineering (Vol. 1980). Amer Inst Physics. https://doi.org/10.1063/1.5044338

National Fire Protection Association, N. (2013). NFPA 1971: Standard on protective ensembles for structural fire fighting and proximity fire fighting. National Fire Protection Association, Quincy, MA(NFPA 1971). https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=1971

Nayak, R., Houshyar, S., & Padhye, R. (2014). Recent trends and future scope in the protection and comfort of fire-fighters' personal protective clothing. Fire Science Reviews, 3(1), 4.

Nazaré, S., & Madrzykowski, D. (2015). A review of test methods for determining protective capabilities of fire fighter protective clothing from steam. National Institute of Standards and Technology Technical Note.

Onofrei, E., Petrusic, S., Bedek, G., Dupont, D., Soulat, D., & Codau, T. C. (2015). Study of heat transfer through multilayer protective clothing at low-level thermal radiation. Journal of Industrial Textiles, 45(2), 222-238.

Pennes, H. H. (1948). Analysis of tissue and arterial blood temperatures in the resting human forearm. Journal of applied physiology, 1(2), 93-122.

Prasad, K., Twilley, W., & Lawson, J. R. (2002). Thermal Performance of Fire Fighters' Protective Clothing. 1. Numerical Study of Transient Heat and Water Vapor Transfer. National Institute of Standards and Technology, Gaithersburg, MD.

Psikuta, A., Frackiewicz-Kaczmarek, J., Frydrych, I., & Rossi, R. (2012). Quantitative evaluation of air gap thickness and contact area between body and garment. Textile Research Journal, 82(14), 1405-1413. https://doi.org/10.1177/0040517512436823

Puszkarz, A. K., Machnowski, W., & Błasińska, A. (2020). Modeling of thermal performance of multilayer protective clothing exposed to radiant heat. Heat and mass transfer, 56(6), 1767-1775. https://doi.org/10.1007/s00231-020-02820-1

Qian, X., & Fan, J. (2006). Interactions of the surface heat and moisture transfer from the human body under varying climatic conditions and walking speeds. Appl Ergon, 37(6), 685-693.

Rahaim, C. P., Oberkampf, W. L., Cosner, R. R., & Dominik, D. F. (2003, 6-9 January 2003). AIAA Committee on Standards for CFD-Status and Plans 41st Aerospace Sciences Meeting, Reno, Nevada.

Raj, P. K. (2008). Field tests on human tolerance to (LNG) fire radiant heat exposure, and attenuation effects of clothing and other objects. Journal of hazardous materials, 157(2-3), 247-259.

Rao, A., Khanna, R., & Gangopadhyay, M. (2012). APPLICATIONS OF FINITE ELEMENTS METHOD (FEM) -AN OVERVIEW International Conference on Mathematical Sciences, Nagpur, India.

Richardson, L. F. (1911). IX. The approximate arithmetical solution by finite differences of physical problems involving differential equations, with an application to the stresses in a masonry dam. Phil. Trans. R. Soc. Lond. A, 210(459-470), 307-357.

Roache, P. J. (1994). Perspective: a method for uniform reporting of grid refinement studies. Journal of Fluids Engineering, 116(3), 405-413.

Roache, P. J. (1998). Verification and validation in computational science and engineering. Hermosa.

Rodríguez-Marroyo, J. A., López-Satue, J., Pernía, R., Carballo, B., García-López, J., Foster, C., & Villa, J. G. (2012). Physiological work demands of Spanish wildland firefighters during wildfire suppression. International archives of occupational and environmental health, 85(2), 221-228. https://doi.org/10.1007/s00420-011-0661-4

Rossi, R. (2005). Interactions between protection and thermal comfort, Cambridge, UK, Woodhead Publishing Limited.

Rossi, R., Indelicato, E., & Bolli, W. (2004). Hot steam transfer through heat protective clothing layers. International Journal of Occupational Safety and Ergonomics, 10(3), 239-245. https://doi.org/10.1080/10803548.2004.11076611

Roy, C. (2004, April 19-24). Verification of Codes and Solutions in Computational Simulation. Proceedings CHT- 04, Norway.

Sacadura, J. F. (2005). Radiative heat transfer in fire safety science. Journal of Quantitative Spectroscopy & Radiative Transfer, 93(1-3), 5-24. https://doi.org/10.1016/j.jqsrt.2004.08.011

Sawcyn, C. M. J., & Torvi, D. A. (2009). Improving Heat Transfer Models of Air Gaps in Bench Top Tests of Thermal Protective Fabrics [Article]. Textile Research Journal, 79(7), 632-644. https://doi.org/10.1177/0040517508093415

Schwer, L. E. (2008). Is your mesh refined enough? Estimating discretization error using GCI. 7th LS-DYNA Anwenderforum, 1(1), 50.

Scott, R. A. (2005). Textiles for protection. Elsevier.

Singer, A. J., Taira, B. R., Lee, C. C., & Soroff, H. (2014). Thermal burns. Rosen's Emergency Medicine: Concepts and Clinical Practice. 8th ed. Philadelphia, PA: Elsevier Saunders.

Song, G. (2003). Modeling thermal protection outfits for fire exposures http://www.lib.ncsu.edu/resolver/1840.16/5766

Song, G. (2007). Clothing air gap layers and thermal protective performance in single layer garment. Journal of Industrial Textiles, 36(3), 193-205. https://doi.org/https://doi-org.ezproxy.utm.my/10.1177%2F1528083707069506

Song, G., Barker, R. L., Hamouda, H., Kuznetsov, A. V., Chitrphiromsri, P., & Grimes, R. V. (2004). Modeling the thermal protective performance of heat resistant garments in flash fire exposures. Textile Research Journal, 74(12), 1033-1040. https://doi.org/10.1177/004051750407401201

Song, G., Cao, W., & Gholamreza, F. (2011). Analyzing stored thermal energy and thermal protective performance of clothing. Textile Research Journal, 81(11), 1124-1138. https://doi.org/10.1177/0040517511398943

Song, G., Chitrphiromsri, P., & Ding, D. (2008). Numerical simulations of heat and moisture transport in thermal protective clothing under flash fire conditions. International Journal of Occupational Safety and Ergonomics, 14(1), 89-106.

Song, G. W., Cao, W., & Gholamreza, F. (2011). Analyzing stored thermal energy and thermal protective performance of clothing. Textile Research Journal, 81(11), 1124-1138. https://doi.org/10.1177/0040517511398943

Su, Y., He, J. Z., & Li, J. (2016). Modeling the transmitted and stored energy in multilayer protective clothing under low-level radiant exposure. Applied

Thermal Engineering, 93, 1295-1303. https://doi.org/10.1016/j.applthermaleng.2015.10.089

Su, Y., Li, J., & Wang, Y. (2017). Effect of air gap thickness on thermal protection of firefighter's protective clothing against hot steam and thermal radiation [journal article]. Fibers and Polymers, 18(3), 582-589. https://doi.org/10.1007/s12221-017-6714-x

Su, Y., Li, R., Yang, J., Song, G. W., & Li, J. (2019). Developing a test device to analyze heat transfer through firefighter protective clothing. International Journal of Thermal Sciences, 138, 1-11. https://doi.org/10.1016/j.ijthermalsci.2018.12.031

Su, Y., Yang, J., Li, R., Song, G., & Li, J. (2020). Experimental study of moisture role and heat transfer in thermal insulation fabric against hot surface contact. International Journal of Thermal Sciences, 156, 106501. https://doi.org/10.1016/j.ijthermalsci.2020.106501

Sun, C., & Fan, J. (2017). Comparison of clothing thermal comfort properties measured on female and male sweating manikins. Textile Research Journal, 87(18), 2214-2223. https://doi.org/10.1177/0040517516669071

Sun, G., Yoo, H., Zhang, X., & Pan, N. (2000). Radiant protective and transport properties of fabrics used by wildland firefighters. Textile Research Journal, 70(7), 567-573.

Talukdar, P., Torvi, D. A., Simonson, C. J., & Sawcyn, C. M. J. (2010). Coupled CFD and radiation simulation of air gaps in bench top protective fabric tests. International Journal of Heat and Mass Transfer, 53(1-3), 526-539. https://doi.org/10.1016/j.ijheatmasstransfer.2009.04.041

Tanda, G. (2016). Skin temperature measurements by infrared thermography during running exercise. Experimental Thermal and Fluid Science, 71, 103-113. https://doi.org/10.1016/j.expthermflusci.2015.10.006

Tannehill, J., Anderson, D., & Pletcher, R. (1997). Computational Fluid Mechanics and Heat Transfer, 2nd edn. Series in Computational and Physical Processes in Mechanics and Thermal Sciences. Taylor & Francis.

Technology Evaluation Center, T. (n.d). Finite Element Analysis (FEA) Software. https://www3.technologyevaluation.com/sd/category/Finite-Element-Analysis-FEA

Tian, M., & Li, J. (2020). A method to predict burn injuries of firefighters considering heterogeneous skin thickness distribution based on the instrumented manikin system. International Journal of Occupational Safety and Ergonomics, 13. https://doi.org/10.1080/10803548.2019.1700665

Tian, M., Wang, Z. L., & Li, J. (2016). 3D numerical simulation of heat transfer through simplified protective clothing during fire exposure by CFD. International Journal of Heat and Mass Transfer, 93, 314-321. https://doi.org/10.1016/j.ijheatmasstransfer.2015.09.027

Torvi, D. A., Douglas Dale, J., & Faulkner, B. (1999). Influence of air gaps on bench-top test results of flame resistant fabrics. Journal of Fire Protection Engineering, 10(1), 1-12. https://doi.org/https://doi-org.ezproxy.utm.my/10.1177%2F104239159901000101

Udayraj, Talukdar, P., Alagirusamy, R., & Das, A. (2014). Heat transfer analysis and second degree burn prediction in human skin exposed to flame and radiant heat using dual phase lag phenomenon. International Journal of Heat and Mass Transfer, 78, 1068-1079. https://doi.org/10.1016/j.ijheatmasstransfer.2014.07.073

Wakatsuki, K., Morii, N., Ogawa, Y., & Tsuji, H. (2013). Influence on Skin Burns by Water Absorbed Station Wear and Underwear in Firefighter Clothing. Advanced Materials Research,

Wang, F., Gao, C., Kuklane, K., & Holmér, I. (2011). Determination of clothing evaporative resistance on a sweating thermal manikin in an isothermal condition: heat loss method or mass loss method. Annals of Occupational Hygiene, 55(7), 775-783.

Wang, Y.-y., Lu, Y.-h., Li, J., & Pan, J.-h. (2012). Effects of air gap entrapped in multilayer fabrics and moisture on thermal protective performance. Fibers and Polymers, 13(5), 647-652. https://doi.org/10.1007/s12221-012-0647-1

Weaver, J. A., & Stoll, A. M. (1967). Mathematical model of skin exposed to thermal radiation (AD0659973

). https://apps.dtic.mil/dtic/tr/fulltext/u2/659973.pdf

Wilcox, D. (2006). Turbulence modeling in CFD (3rd Edition). D C W Industries; 3rd Edition.

Wright, N. T. (2003). On a Relationship Between the Arrhenius Parameters from Thermal Damage Studies. Journal of Biomechanical Engineering, 125(2), 300-304. https://doi.org/10.1115/1.1553974

Wu, M., & Chow, W. (2013). A review on fire-resistant glass with high rating. J Appl Fire Sci, 23, 59-76.

Zainol, Z. N., Md Tap, M., & Mohamed Kamar, H. (2018, 12-13 May 2018). Application Bioheat Equation For Heat Transfer Model of Firefighter's Burn Injury. 2nd Asia International Multidisciplinary Conference AIMC 2018, Johor Bahru

Zhai, L. N., & Li, J. (2015). Prediction methods of skin burn for performance evaluation of thermal protective clothing. Burns, 41(7), 1385-1396. https://doi.org/10.1016/j.burns.2015.02.019

Zhu, F. L., & Li, K. J. (2011). Numerical Modeling of Heat and Moisture Through Wet Cotton Fabric Using the Method of Chemical Thermodynamic Law Under Simulated Fire. Fire technology, 47(3), 801-819. https://doi.org/10.1007/s10694-010-0201-x

Zhu, F. L., & Zhang, W. Y. (2009). Modeling Heat Transfer for Heat-resistant Fabrics Considering Pyrolysis Effect under an External Heat Flux. Journal of Fire Sciences, 27(1), 81-96. https://doi.org/10.1177/0734904108094960

Zhu, F. L., Zhang, W. Y., & Song, G. W. (2008). Heat transfer in a cylinder sheathed by flame-resistant fabrics exposed to convective and radiant heat flux. Fire Safety Journal, 43(6), 401-409. https://doi.org/10.1016/j.firesaf.2007.11.007

Zhu, F. L., & Zhou, Y. (2013). Modelling heat-moisture transport through firefighters' protective fabrics from an impinging flame jet by simulating the drying process. Fibres & Textiles in Eastern Europe, 5(101), 85-90.

LIST OF PUBLICATIONS

Scopus Indexed Journal

1. Zainol, Z. N., Md Tap, M., Mohamed Kamar, H., & Kamsah, N. (2019). Heat Transfer Model to Predict Human Skin Temperature under Comfort Level by using Bioheat Equation. *International Journal of Online and Biomedical Engineering*, *15*(10), 52-64.
2. Zainol, Z. N., Md Tap, M., Mohamed Kamar, H., & Kamsah, N. (2019). Heat Transfer Model for Firefighter's Burn Injury. *Indian Journal of Public Health Research & Development*, *10*(6), 1510-1515. https://doi.org/10.5958/0976-5506.2019.01512.2
3. Zainol, Z. N., Tap, M. M., Kamar, H. M., & Kamash, N. (2019). The effect of air gap and moisture for the skin burn injury of the firefighter's personal protective clothing. *International journal of engineering and advanced technology*, *9*(2), 4048-4054. http://dx.doi.org/10.35940/ijeat.B4943.129219
4. Zainol, Z. N., Tap, M. M., Kamar, H. M., & Kamash, N. (2019). Heat Transfer Model for Steam Burn Injury among Firefighters. *International Journal of Recent Technology and Engineering (IJRTE)*, *8*(1S), 176-182. https://www.ijrte.org/wp-content/uploads/papers/v8i1S/A10250581S19.pdf

Proceedings

1. Zainol, Z. N., Md Tap, M., & Mohamed Kamar, H. (2019). Prediction human skin temperature in comfort level. Science Proceedings Series, 1(3). https://doi.org/10.31580/sps.v1i3.857
2. Zainol, Z. N., Md Tap, M., & Mohamed Kamar, H. (2019). Steam Burn Injury Model of Firefighters Personal Protective Clothing. Science Proceedings Series, 1(1). https://doi.org/10.31580/sps.v1i1.511