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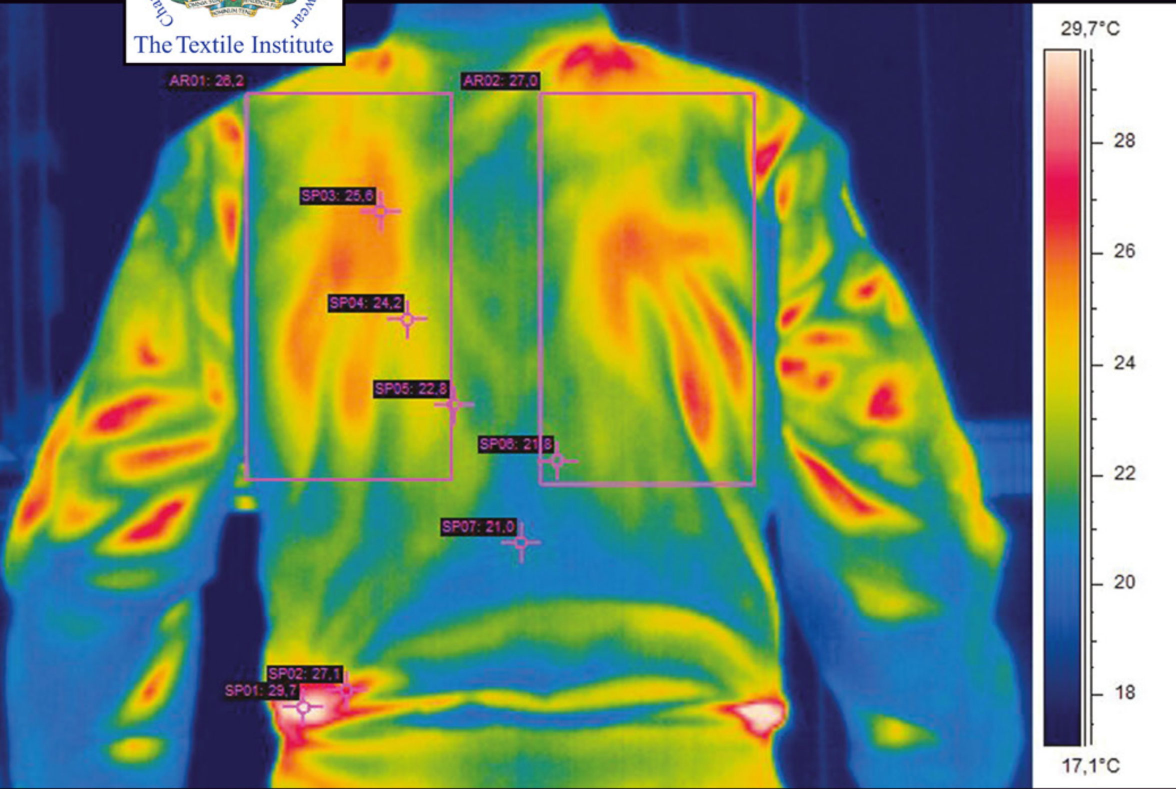

STANDARD METHODS FOR THERMAL COMFORT ASSESSMENT OF CLOTHING

Ivana Špelić • Alka Mihelić-Bogdanić
Anica Hursa Šajatović

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Authored by
Ivana Špelić, Alka Mihelić-Bogdanić,
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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed on acid-free paper

International Standard Book Number-13: 978-1-138-39147-5 (Hardback)
International Standard Book Number-13: 978-1-138-39098-0 (Paperback)

Library of Congress Cataloging-in-Publication Data

Names: Špelić, Ivana, author. | Bogdanić, Alka Mihelić, author. | Šajatović, Anica Hursa, author.
Title: Standard methods for thermal comfort assessment of clothing / Ivana Špelic, Alka Mihelić Bogdanić, Anica Hursa Šajatović.
Description: First edition. | Boca Raton, FL : CRC Press/Taylor & Francis Group, 2018. | Includes bibliographical references and index.
Identifiers: LCCN 2018061308| ISBN 9781138391475 (hardback : alk. paper) | ISBN 9781138390980 (pbk. : alk. paper) | ISBN 9780429422997 (ebook)
Subjects: LCSH: Clothing and dress--Testing--Standards. | Textile fabrics--Testing--Standards. | Fashion design--Standards. | Clothing and dress--Physiological aspects. | Temperature--Physiological aspects. | Human comfort.
Classification: LCC TT499 .S64 2018 | DDC 646/.3--dc23
LC record available at https://lccn.loc.gov/2018061308

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Preface

Sometimes we are unaware of how things can work out and how someone's faith in you can change the course of your everyday life. When we received the email with a proposal to write this book, there was no one happier than we were nor more afraid of the work that should be done in the future. You grow as a scientist reading about the great ideas written by people who had instilled you with love and admiration for both the knowledge they provided and the area of research. This book is merely a small portion of knowledge, donated by many of the researchers in the area of human thermal comfort, and our way of thanking them for their selfless work.

It was an honour and a privilege to write this book. The advances over the last few decades forced regulation improvements and international standards development in the area of thermal comfort. Since clothing is considered as one of the most important factors in modelling heat losses from the human body, thermal comfort assessment is a key element in guarding the human body while interacting with sometimes harsh environmental influences. Here is where the national and international standards provide help through the non-obligatory guidance and promotion of safe and reliable clothing thermal comfort assessment. For many decades, the study of human thermal comfort aimed to prevent health problems, cold-related injuries and thermal stress. Since comfort involves various contributing factors, both the psychological, physiological and physical, the study of thermal comfort assessment addresses many concerns. Since the beginnings of the study of the thermal comfort in humans, born in the early decades of the twentieth century, the multidisciplinary approach for defining problems and finding the optimal solutions is the only possible way. Through the selfless work of practitioners and scientists all over the world, we have found a way to cope with our environment. The development of standards and the unification of testing methods is of crucial significance for fostering thermal comfort research to serve us all in an objective, cost-reducing and health-protective manner.

Textile Institute Professional Publications

The aim of the ***Textile Institute Professional Publications*** is to provide support to textile professionals in their work and to help emerging professionals, such as final year or Master's students, by providing the information needed to gain a sound understanding of key and emerging topics relating to textile, clothing and footwear technology, textile chemistry, materials science and engineering. The books are written by experienced authors with expertise in the topic, and all texts are independently reviewed by textile professionals or textile academics.

The textile industry has a history of being both an innovator and an early adopter of a wide variety of technologies. There are textile businesses of some kind operating in all counties across the world. At any one time, there is an enormous breadth of sophistication in how such companies might function. In some places where the industry serves only its own local market, design, development and production may continue to be based on traditional techniques, but companies that aspire to operate globally find themselves in an intensely competitive environment, some driven by the need to appeal to followers of fast-moving fashion, others by demands for high performance and unprecedented levels of reliability. Textile professionals working within such organisations are subjected to a continued pressing need to introduce new materials and technologies, not only to improve production efficiency and reduce costs but also to enhance the attractiveness and performance of their existing products and to bring new products into being. As a consequence, textile academics and professionals find themselves having to continuously improve their understanding of a wide range of new materials and emerging technologies to keep pace with competitors.

The Textile Institute was formed in 1910 to provide professional support to textile practitioners and academics undertaking research and teaching in the field of textiles. The Institute quickly established itself as the professional body for textiles worldwide and now has individual and corporate members in over 80 countries. The Institute works to provide sources of reliable and up-to-date information to support textile professionals through its research journals, the ***Journal of the Textile Institute***[1] and ***Textile Progress***,[2] definitive descriptions of textiles and their components through its online publication ***Textile Terms and Definitions***,[3] and contextual treatments of important topics within the field of textiles in the form of self-contained books such as the ***Textile Institute Professional Publications***.

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2. http://www.tandfonline.com/action/journalInformation?show=aimsScope&journalCode=ttpr20
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Author Bios

Ivana Špelić, PhD, is a Postdoctoral Researcher at the University of Zagreb, Faculty of Textile Technology, Zagreb, Croatia. The areas of her special research interests are heat transfer in a body–clothing–environment system, applications of CAD systems for reverse engineering of human body modelling and thermal properties of clothing, protective clothing, energetics, technical thermodynamics and the application of alternative and renewable energy sources in textile and clothing industry.

Alka Mihelić-Bogdanić, PhD, is a Full Professor at the University of Zagreb, Faculty of Textile Technology, Zagreb, Croatia. The areas of her special research interests are heat recovery, energetics, technical thermodynamics, energy saving and management in industry as well as the application of alternative and renewable energy sources in the textile and clothing industry. She currently works as a member in the national research project involving thermophysiological properties of textile and footwear.

Anica Hursa Šajatović, PhD, is an Associate Professor at the University of Zagreb, Faculty of Textile Technology, Zagreb, Croatia. The areas of her special research interests are footwear production technology and protective footwear, protective clothing and clothing systems for protection from heat and fire and application of numerical modelling in garment production processes. She is a member of the technical committee of the Croatian Standards Institute in the area of protective clothing as well as leather and footwear.

1 Introduction

Vast knowledge of the principles of human physiology is required by practitioners for conducting most of the tests and measurements involving clothing. Since clothing is merely a part of the greater body–clothing–environment system, every single component of this system is connected and dependent on the other.

The heat and mass transfer pathways through textile and clothing structures are complex, and often a few simultaneous transport processes occur. Since clothing is a basic human need for survival, along with the food and shelter (*Textile Technology*, 2006), scientists and industry practitioners put a lot of effort into scientific research and technological improvements for producing textile structures and clothing for different end users and applications. Continuous improvements emerge on a daily basis for assisting with the thermal and moisture regulation of the human body through fibres, yarns and fabric construction engineering, and by developing special protective clothing for different environmental conditions and working environments.

New fabric and other textile materials are continuously designed in order to protect the human body from outside agents and to (*Heat & Mass Transfer in Textiles*, 2011):

1. Modify the water vapour and moisture loss rate of the insensible perspiration thus assisting the skin in conserving essential levels of body fluids or to cool the body.
2. Modify the heat loss rate of to keep the body in a cold environment at its critical internal temperature.
3. Keep the moisture penetration in the form of the rain and snow from the outside ambient to the skin and causing the body to become too cold.
4. Absorb solar hazardous electromagnetic waves and substances, such as ultraviolet radiation and toxic gases.
5. Block the penetration of harmful fluids such as blood-containing pathogens.

When it comes to clothing, its basic role is to modify the heat transfer between the human body and the environment. In this manner, the design process should always consider the intended usage and final purpose of the clothing. The other important factor to consider is the individual variations in heat exchange rate. The heat exchange rate varies greatly from person to person, for the various activities concerned and for the type of clothing worn (Gagge and Nishi, 1977). Finding common ground between the functional details needed, the production costs and the optimum design, which can provide the intended protection for the average consumer, involves the integration of various requirements in an all-around multidisciplinary approach.

In the past, testing of specialised protective clothing mainly concentrated on the material requirements and a few important clothing properties, although an important advantage of material test methods are that they are designed to produce accurate and reproducible results, both within and between laboratories, at minimal cost (Havenith and Heus, 2004).

Over the last few decades, clothing and textile design was driven by government and military needs for functional, protective and well-fitted garments, and performance-based garments for sport clothing companies. A new problem-solving design research area emerged focusing on both quantitative and qualitative methods in addition to practice (Bye, 2010).

Contemporary clothing design follows the crossover, multidisciplinary approach to clothing design involving the cooperation of two or more different areas for dealing with the more psychological needs of the complex survival environment. Growing clothing design requirements impose great diversification in the designs. The multidisciplinary design process incorporates human body engineering, medicine, chemical technology, nanotechnology, biotechnology, optics and many other disciplines. Besides the traditional people-oriented principle, the contemporary clothing design is fostered by new innovative material developments, the need for higher performance, development of intelligent clothing, the assistance of virtual technology and the need for sustainable and ecological development (Chunyan and Yue, 2014). Various effects need to be taken into account during the design development and testing of the protective clothing. These are the effects of the manufacturing process on the material's properties (stitching, seams, treatments), the effects of clothing design, sizing and fit, the effect of the interaction of the clothing with other components or gear and how the clothing performs in actual use (Havenith and Heus, 2004). The trend of developing multifunctional fashion garments, defined as clothing or clothing systems that allow adaptation to diverse social situations or weather conditions, or simply as having different characteristics for different body areas in order to have different functional features, resulted in new design requirements. One of the basic requirements of clothing design is the issue of comfort (Cunha and Broega, 2009).

In the light of thermophysiological comfort, clothing generally has to be designed to (Angelova, 2016; Vecchi et al., 2017):

1. Protect the human body from weather conditions.
2. Protect from cold and solar radiation.
3. Provide a protective barrier against heat flows (open fire and high temperatures).
4. Provide sufficient comfort in a physical and psychological sense, regardless of the type of activity.

The development of standards related to thermal comfort and the unification of testing methods are of crucial significance to the global market. This allows for clear communication of the product's performance, as well as allowing comparison between products and their materials from different producers. Information, requirements and quality control, which are described in international standards, provide applications for specific market segments and ensures that consumers' needs are fulfilled worldwide. Unlike regulations, which are general laws that cover an entire sector rather than a single product, standards are more complex. Regulations typically set out only a general framework while standards are voluntary but provide more detail on rules, guidelines or characteristics for a product or process. In the absence of an official international standard, one can also use standards from the national organisation for standardisation.

The current definitions of standards always emphasise their voluntary nature. The *Agreement on Technical Barriers to Trade* by the World Trade Organization defines a standard as a document approved by a recognised body *providing for common and repeated use rules, guidelines or characteristics for products or related processes and production methods compliance with which is not mandatory* (*Agreement on Technical Barriers to Trade*, 1995). Similar terminology is also visible in the ISO definition of standards. In *ISO/IEC Guide 2*, a standard is defined as a *document established by consensus* and approved by a recognised body, providing for common and repeated use rules, guidelines, or characteristics for activities or their results aimed at the achievement of the optimum degree of order in a given context. The guide defines standardisation as the activity of establishing – with regard to actual or potential problems – provisions for common and repeated use aimed at the achievement of the optimum degree of order in a given context (*ISO/IEC Guide 2*:2004).

The standards provide the establishment of unique and generally accepted guidelines, methods and regulations, which define the requirements for production processes, quality control and the product itself. They also provide a uniform approach to doing something through open access for the general good. The adoption of standards should support efficiency and overall cost reduction through competition while ensuring product quality, interoperability, safety and reliability. Standards represent a consensus between experts on the best way of doing something. They do not require an inventive step; rather, they document 'good practice' (Taylor and Kuyatt, 1994; Hatto, 2001).

There are a vast number of standards currently in usage around the globe, but only the ISO standards are considered as truly international standards. Since states and governments cannot be members, the ISO is best described as a centrally coordinated global network comprising hundreds of technical committees from all over the world and involving thousands of experts representing industries and other groups for developing and regularly maintaining technical standards. The ISO has grown into the world's largest and most widely recognised standards development organisation (O'Connor, 2015). The ISO's influence is exercised due to size, popularity and recognition. The World Trade Organization (WTO) placed the ISO with a status of the world's 'trade-legal' organisation (Morikawa and Morrison, 2004).

The ISO is formed of a global network of national standards bodies and serves as a global network of the world's leading standardisers. As a leading international organisation, the ISO is nowadays one of the most significant generators of contemporary analysing standards, although none of the international associations mentioned does the product testing itself. Most of the European national standards organisations are simultaneously members of the ISO such as the BSI (British Standards Institution), the DIN (German Institute for Standardization), the SNV (Swiss Association for Standardization), etc. There are also American national standards organisations, which market their products internationally, the ASTM and ANISI/ASHRAE. Thanks to the work performed by these organisations, nowadays there is around 19,500 ISO standards, 12,000 ASTM standards and a few regular ASHARE publications in usage (Špelić et al., 2016).

The advance in technology during and after the Industrial Revolution was accompanied by simultaneous progress in standards development, both in terms of scope and number. A great deal of standards similar to technical specifications emerged as a means of making mass production economically viable and globally applicable. The standardisation of production methods and products stimulated rapid business adaptation (*Standardization: Fundamentals, Impact, and Business Strategy,* 2010). However, standards should be continually reviewed in terms of new knowledge and future requirements to provide the best available methods for the future (Parsons, 2013).

There is still much work to do since there are almost no evident standards for clothing aimed at protecting against cold environments in comparison to standards for clothing aimed at protecting against heat and flames. Another evident flaw is the lack of any standards that address the requirements for everyday clothing, which doesn't fall in the scope of the protective clothing, but there is still great need to specify minimum requirements in order to produce optimum protection against cold.

This book is arranged into nine affiliated chapters. The first chapter is introductory and gives insight to the basic themes covered in the book. The second chapter provides detailed insights on human thermoregulation, from fundamental principles to different approaches in explaining the basic concepts of thermoregulation in humans. The focus is to explain the physiology of thermoregulation in humans that lies in the versatile description of the nervous system, temperature control mechanisms and energy transport modes. Chapter 3 covers the basic principles of a thermal comfort study, heat and moisture transmission through textiles and clothing, the function of clothing in preventing heat losses and factors influencing the ability to maintain a satisfactory thermal state. Chapters 4 to 9 discuss the details of thermal comfort standards: the globally accepted test methods for textile and clothing comfort testing; the basic principles and the significance of comfort standards; the methodology and reasons for creating standards; stakeholders, voting structure and standardising bodies; past, current and future development in this area; coding and naming the standards and last but not least everything you need to know on thermal comfort standards.

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2 Behind the Scenes *Thermal Regulation in Humans*

Humans are *homeotherms* (also called *endotherms*), so they have the ability to regulate their internal body temperature, unlike *poikilotherms* (also called *ectotherms*), which do not regulate their internal body temperature and depend on environmental temperature. In humans and homeothermic animals, there are two thermoregulation functions. First, the thermoregulation function counteracts external and internal temperature excitations, which are capable of temperature homeostasis and pose a danger for life. Second, the thermoregulation function serves to level out small but continuously arising internal and external temperature excitations (Ivanov, 2006).

The human body's internal body temperature is relatively stable over a broad range of ambient conditions. All of the energy contained in ingested food ultimately transforms into heat, and the rest to work performed on the environment or growth. The human thermoregulatory system creates an internal environment in which reaction rates are relatively high and avoids the pathologic consequences of wide deviations in body temperature. To maintain a relatively constant body temperature requires a balance between heat production and heat loss (Hulbert and Else, 2000; Boron and Boulpaep, 2012).

Due to the intrinsically high metabolic rates of their tissues, endotherms can maintain high and constant body temperatures (Hulbert and Else, 2000).

The body's thermoregulatory system consists of two intertwined components, a warm internal core and a cooler outer shell (mostly the skin). The body's core temperature is one of the most tightly regulated parameters of human physiology, but there are slight daily variations due to circadian rhythm, and monthly variations due to women's menstrual cycles (Kurz, 2008; Sessler, 2016). Humans regulate their internal body temperature, called the body's core temperature or temperature of the deep tissue, within a narrow range near 37°C, which usually remains constant within ±0.6°C, despite the variations in outside environmental temperature. The outer shell is not as strictly regulated within narrow limits because the environment greatly influences temperature alterations. In a warm environment, the shell may be less than 1 cm thick, but with humans conserving heat in a cold environment it may extend several centimetres below the skin (Witzmann, 2013). The skin temperature rises and falls, due to the environmental influences but is important for the ability to lose heat to the surroundings (Guyton and Hall, 2016).

The thermal interaction of the human body with the environment involves two simultaneous processes. One is heat transfer, which includes radiation, convection, conduction, evaporation and respiration, and the other is self-regulation in the form of vasoconstriction, vasodilation, shivering and sweating (Cheng et al., 2012). Aside from the subconscious mechanisms for body temperature control, the body uses behavioural control of temperature mechanisms (Guyton and Hall, 2016).

The thermoregulatory responses in cold environments serve to conserve heat within the body (cutaneous vasoconstriction) and to generate heat (shivering and non-shivering thermogenesis). Active regulation of body temperature is almost absent in thermoneutral environments, as heat production equals heat loss. In warm and hot environments, the human thermoregulatory mechanisms work to lose heat (cutaneous vasodilatation and sweating) (Charkoudian, 2016). There are two sources that contribute to heat accumulation inside the human body: internal heat (produced by the metabolism) and external heat (environmental heat), absorbed mainly due radiation and convection (Shapiro and Epstein, 1984).

Humans are more sensitive to danger from cold than from heat as presumed by the preponderance of cold spots over warm spots, and the shallower depth of cold spots relative to the skin surface (Arens and Zhang, 2006). Humans are able to thermal adapt to environments, due to prior thermal exposure affecting their thermal perception. Thermal adaptation significantly affects thermal comfort (Du et al., 2018).

2.1 THERMODYNAMICAL ANALYSIS

The word exergy was introduced by Slovenian scientist Zoran Rant (Kitanovski and Poredoš, 2016). Exergy is maximal technical amount of work, which can be obtained from the internal (intrinsic) energy of the substance. Exergy explains how much of the internal energy can be converted to the maximal work. The exergy is the measurement of the quantity of energy (Rant, 2001).

Energy analysis is a method of assessing the way energy is used in an operation involving the physical or chemical processing of materials and the transfer and/or conversion of energy, usually by performing an energy balance, based on the principle of the conservation of energy, and evaluating energy efficiencies. The exergy analysis method is based on both the 1st law of thermodynamics and the 2nd law of thermodynamics, indicating the locations of energy degradation in a process and quantifying the quality of heat in a waste stream. The exergy is the maximum theoretical useful work obtainable as the systems draw closer towards equilibrium, where heat transfer occurs only with the environment. Exergy depends on the properties of both a matter or energy flow and the environment, while the energy is independent of the environmental properties. This is a measure of the ability to do work of the great variety of streams (mass, heat, work) that flow through a system. Exergy equals zero when the system is in complete equilibrium with the environment. Exergy can be destroyed and generally is not conserved. The value of exergy can never be negative. Unlike energy, which cannot be destroyed nor produced (in accordance with the 1st law of thermodynamics), exergy can be neither destroyed nor produced in a reversible process but is always consumed in an irreversible process. Since energy is only a measure of quantity, exergy is a measure of both quantity and quality and appears in many forms (e.g. thermal exergy). It is measured on the basis of work or ability to produce work. Energy flows into and out of a system with mass flows, heat transfers and work interactions. Exergy can be transferred by exergy transfer associated with