

Underwear for Protective Clothing Used by Foundry Worker

DOI: 10.5604/12303666.1215533

Lodz University of Technology,
Faculty of Material Technologies
and Textile Design
Institute of Architecture of Textiles,
ul. Żeromskiego 116, 90-924 Łódź, Poland
E-mail: agnieszka.cichocka@p.lodz.pl

Abstract

Foundry worker activity involves remaining in a high temperature while working close to a melting furnace. Special clothing made from aluminised fabrics for this action ensures protection against high temperature. However, the problem is that the existing so far suits have not been breathable. This paper presents the utility comfort parameters of underwear goods which can be used under protective clothing. The special structure of underwear should assure the maintenance of constant temperature of the body. In order to compare the basic functions, namely ensuring comfort of use, innovative underwear products underwent measurements on a thermal manikin. Moreover a comparison between new raw material solutions of underwear and traditional cotton underwear was made. Additionally the air and water vapour permeability of knitted fabrics were measured. The aim of the study was also to determine such properties as the thermal insulation, air and water vapour permeability of underwear products that influence the physiological comfort of foundry workers in order to choose the best one for foundry worker activity.

Key words: thermal manikin, thermal insulation, knitted underwear, protective clothing.

Introduction

Protective clothing designed for hot environments should provide protection against heat radiation. A foundry worker at a melting furnace heated to 1500 - 1600 °C. Opening the blast furnace for approximately 2 - 3 minutes causes heat radiation on the worker's body with a temperature of 40 - 60 °C [1]. Industrial halls are rarely heated and generally the conditions of the ambient temperature are close to 20 °C or even lower. Therefore in the time of working in hot places, temperature difference between the back and front part of the body changes between 20 - 40 °C [2]. Foundry worker's suits consist of three layers: outer layer protective clothing made of aluminised glass fabric and flame-retardant wool lining, flame-retardant impregnated clothing and underneath - underwear.

In the case considered we decided to focus only on underwear products and not on modifications of suits for foundry works.

It should also be emphasised that the work undertaken was not devoted to elaborate optimised stitches and structures, but to selecting from underwear available on the market i.e. the best one suitable for extraordinarily strong and controversial conditions. It was the first step to improve the worker's physiological comfort while wearing impermeable suits. The next step can be a trial to advance the feeling of comfort with the suit's construction. The task of underwear is to provide good sweat transportation from the human body to outer layers

of clothing. Moreover underwear should reply on temperature changes which occur during the foundry worker activity. Underwear with high thermal properties as compared to cotton underwear ought to ensure maintenance of natural body heat and immediate perspiration [3]. It should be emphasised here that the goal set for this research was very difficult as opposite features of the underwear should be maintained, which is not only good thermal insulation against cold but also good air and water vapour permeability. To fulfil this task, measurement was made according to the proper standards and with the use of a manikin. Measurements of the thermal insulation of underwear knitted with long sleeves were on a thermal manikin. The air permeability (PN-EN ISO 9237 [3]) and water vapour permeability (PN-71/P-04611 [4]) of synthetic and cotton underwear products were analysed. These measurements allowed for assessment of the physiological comfort parameters of a human being in synthetic underwear taking into consideration the mechanism of heat exchange between the human organism and the environment.

The basic parameters describing heat exchange through textiles is thermal insulation and water vapour permeability. The thermal insulation of textiles expresses the clothing's ability to reduce heat absorption. There is a possibility of heat exchange by conduction, convection and radiation. The amount of heat transferred by the clothing due to conduction depends on the clothing area and difference in temperature between

Table 1. Characteristics of underwear products.

Underwear	Knit stitches	Mass per square meter, g/m ²	Thickness, mm	Wale, count/1 cm	Course, count/1 cm	Composition
A	Plated plain with jacquard	155	0.70	16	18	54% PA, 44% PES, 2% Elastane
B	Relief plain	101	0.90	15	17	70% PP, 30% PA
C	Plated plain	158	0.71	15	22	54% modal protect, 27% cotton, 19% PA
D	Plated plain	220	0.81	10	17	100% cotton

the human skin and outer clothing layers [5, 6]. The thermal insulation of clothing packages depends on the kinds of raw materials, clothing construction, and the amount of still air confined between the clothing layers. The unit of clothing thermal insulation is clo, where:

$$1 \text{ clo} = 0.155 \text{ m}^2\text{K/W}$$

1 clo determines the thermal insulation of clothing necessary for maintaining the thermal balance between the human organism and the environment.

The problem of choosing the best underwear product available on the market for a foundry worker, considered in the paper, is very complex, really difficult, and it is not easy to find a good solution to improve physiological comfort while working in high temperature. There are not many studies where researchers try to find out, how different kinds of underwear could influence the physiological comfort of the human body in protective clothing. In this case, on the one hand, there is a need to provide good protection against high temperature, but on the other, the aim is to allow water vapour to be transported out from the human skin. Furthermore during work the foundry worker is exposed not only to high temperature, but also temperature differences, which is why the layer of underwear should allow for quick water vapour transport and at the same time provide good heat insulation. The focus of this work was to achieve optimal thermal comfort using different kinds of underwear; whereas the other parts of protective clothing remain unchanged. Moreover the purpose of the research takes into account the comparison of thermal insulation of underwear products made from cotton and synthetic fibres without taking into account the stitch structure or types of raw material.

Due to the negative influence of the work environment on the human being, thermal manikins were built which simulate human body sensation. Thermal manikin shapes are similar to the human silhouette [7]. Originally manikins had a very

primitive construction. The first thermal manikin was constructed for the needs of the US army, consisting of only one segment. Nowadays manikins simulate the human body very precisely, consisting of 15 to 30 segments controlled independently. Also available are sweating manikins, and the present techniques allow for real simulation of human body movements [8]. The application of thermal manikins is an important solution for research on different kinds of clothing. Thermal insulation determined by measurement on a manikin allows to obtain precise and comparable results in the given conditions.

Material

The characteristics of underwear products are given in *Table 1*.

All underwear products are seamless, produced from a thin two-layer knit. All underwear measured (T-shirt with long sleeves) were of M size from a unisex collection [11]. The underwear products used for tests were commercially available. Underwear chosen for tests are differentiated in the aspect of basic parameters. During the research, the ability of each underwear with long sleeves to provide thermal comfort and its water vapour permeability capability were verified.

The innovation of underwear products relies, among others, on the application of raw material, which allows to provide a feeling of physiological comfort at a higher level than in the case of traditional cotton underwear. Synthetic fibres used in innovative underwear products allow air and moisture transportation through textiles. These solutions are achieved not only due the selection of appropriate hydrophilic fibres, the use of different structural parameters of underwear also provide a variety of thermal insulation values. The relief stitch allows to obtain a spatial structure of the knitting product, creating an extra space between the human skin and fabric. Thanks to the 3D structure, the air permeability is

transferred faster to the environment than in the case of a one layer structure.

A special knitwear structure enabled to create separate zones that differ by stitch. The plated stitch contains in its structure two types of yarns, from which goods are produced. Knitwear fabric produced in this manner caused greater spaces between stitches, so that it can provide a higher value of thermal insulation than traditional cotton underwear. Jacquard stitches include links, which are characterised by a lower compressibility, providing additional ventilation in areas of increased sweating. Products made with this type of stitch may have higher air permeability.

Methodology

To measure the thermal insulation of the new types of underwear products, a thermal manikin - "Pernille" of the PT-Teknik Company from Denmark, was used. Thanks to the realistic simulation of the human silhouette, it is possible to obtain results for the whole body area. The manikin consisted of the following body parts: the head, chest, tummy, backside, pelvis, arms, hands, legs and feet.

The advantage of using a thermal manikin is that it is an objective way of heat exchange assessment as well as the repeatability and precision of measurement. The skin temperature of the manikin was 34 °C, and the temperature inside the manikin body - 36.6 °C according to PN-EN ISO 15832:2006 "Clothing. Physiological properties. Thermal insulation measurement with the use of thermal manikin" [8, 9]. The measurements were done in a climatic chamber of ambient temperature 20 ± 5 °C. During the examination the manikin was dressed in the selected underwear (T-shirt with long sleeves). The whole manikin's body was heated and covered by the underwear. For calculation, only the results obtained from the upper part of the manikin's body, like the chest, back, shoulders, arm and forearm were used. The manikin remained in a static position. For calcula-

tion of the thermal insulation (I_{Tr}) the serial model was used, which is described as follows:

$$I_{Tr} = \frac{(T_s - T_a) \times A}{H_c}, \text{ in } \frac{m^2 \cdot K}{W} \quad (1)$$

where:

A – total surface area of the manikin, m^2 ;

H_c – power of heat flux density, W;

T_s – mean skin temperature, $^{\circ}C$;

T_a – mean ambient temperature inside the climate chamber, $^{\circ}C$.

$$T_s = \sum f_i \cdot T_{si} \text{ in } ^{\circ}C \quad (2)$$

where:

f_i – part of the total surface area which is the area of the manikin segment chosen, m^2 ;

T_{si} – skin temperature of manikin segment chosen, $^{\circ}C$.

$$H_c = \sum H_{ci} \text{ in } W \quad (3)$$

where,

H_{ci} – power of heat flux density of manikin segment chosen, W.

For the aforementioned underwear products, the water vapour permeability was also measured according to the PN-71/P-04611 standard. This property determines the amount of water vapour which will be transported from the manikin body to the fabric area in a unit of time. During the measurements, the normal climate in the laboratory should be set and assured. Pots with samples should be placed in a water bath of temperature $37^{\circ}C$ [4, 10]. This measurement informs

us what amount of sweat will evaporate outside the underwear.

The next test was the air permeability measurement. Air permeability is the volume of air passing through a fabric under pressure depending on the fabric porosity, and can be used to provide information on fabric breathability. Fabrics with different surface textures on each side can have different air permeabilities depending on the direction of air flow.

During the measurement, the amount of air going through samples of 20 cm² diameter is determined (PN-EN ISO 9237). The pressure difference between both sample sides is given [3]. During the measurement, the air which had gone through the sample from the outside to the inside was measured. A lower amount of air which comes from the environment means better protection against heat loss. Underwear is worn under daily clothing; hence it is important to enable human skin to breath.

Results and discussion

Based on the measurements on the thermal manikin using the serial model of result calculation, the highest value of thermal insulation was obtained by underwear C (*Figure 1.a*), while underwear A and B achieved a similar (but lower than underwear C) level of heat insulation. Comparing to underwear D, for

which the thermal insulation value was taken as 100%, underwear A has a better heat insulation (higher about 42%), while underwear B is higher by about 40%. The thermal resistance value for underwear C was about 65% higher than for underwear D, which means that the underwear products made of synthetic fibres provide thermal insulation at a higher level in comparison to underwear D made from cotton.

Results of water vapour permeability and air permeability show that underwear B received results at the highest level. A 3D relief plain stitch applied in the underwear provides the best feeling to the human body; and therefore heat exchange by conduction occurs the fastest. The 3D stitch used in underwear B is more spacious than the other products tested. Underwear B is characterised by the lowest weight, namely its structure is looser than that of the other underwear; but its thickness is greater. Underwear B is supposed to provide the immediate removal of moisture from the skin, providing better water vapour permeability. However, the high air permeability will affect the smaller value of heat insulation more than for the rest of products tested. Water vapour permeability for underwear A reached the smallest value in comparison to the rest of underwear products (*Figure 1.b*). Underwear C allows for water vapour transport in similar quantities as for underwear A (*Figure 1.c*).

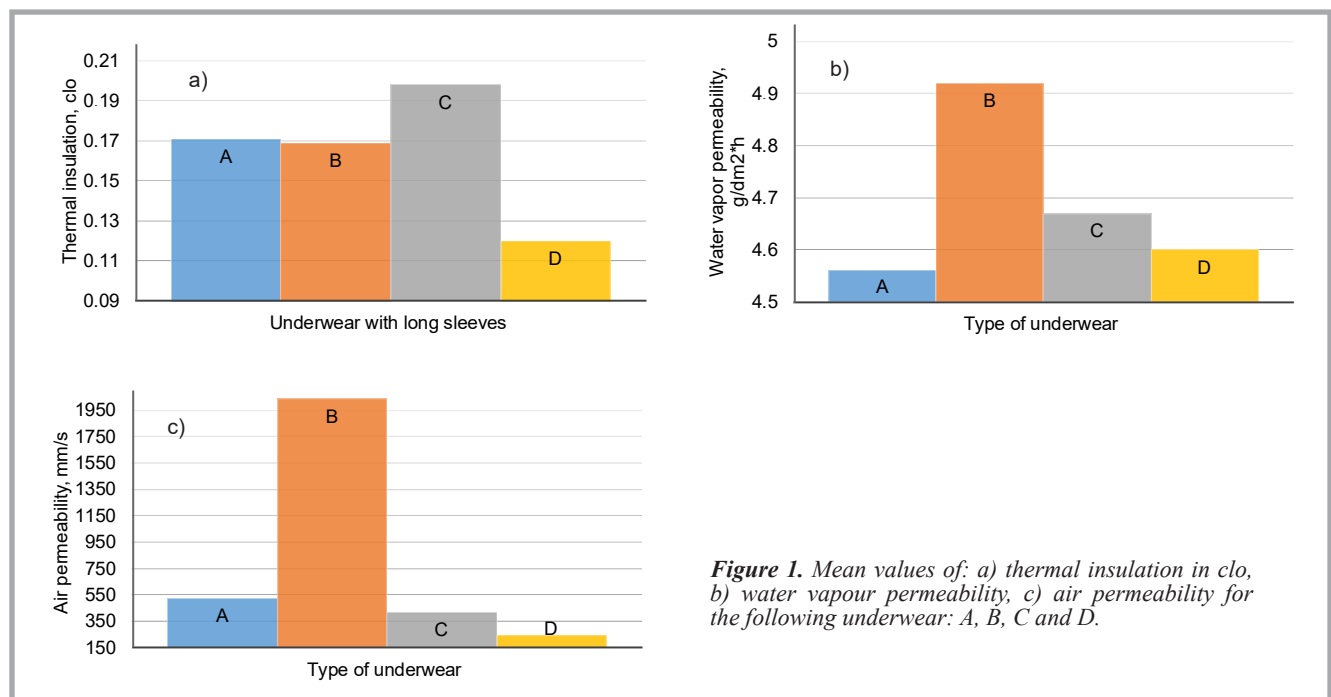


Figure 1. Mean values of: a) thermal insulation in clo, b) water vapour permeability, c) air permeability for the following underwear: A, B, C and D.

It seems that underwear for foundry workers with a good thermal comfort should have a lower air permeability value considering that the flow of hot air from the outside to the inside of the clothing set is undesirable. A bigger amount of air can easily get through underwear B, which results from the higher heat loss compared to the other products. Air permeability for underwear products A and C achieved similar values. It can be observed that the value of air permeability for underwear C is higher by approximately half compared to that for cotton underwear.

Summary

The measurements carried out allow for the assessment of physiological comfort parameters of different underwear products covering the upper part of the body. Comparison of thermal insulation for synthetic types of underwear (A, B, C) and for traditional cotton underwear D allow to state that the new ones are superior because they better protect against heat radiation in environmental conditions.

Each of the underwear made from synthetic fibres achieved a higher thermal insulation value than for the cotton one, which means that underwear made of synthetic fibres will provide comfort at a higher level in comparison to conventional (traditional) cotton underwear. Water vapour and air permeability enable comparison of new underwear products. Underwear (T-shirt with long sleeves) A and B provide protection against heat radiation at a similar level, whilst in the case of underwear C it is higher. On the other hand, underwear B provides better air permeability than underwear A and C in the same conditions. It is obvious that the underwear must be worn under clothes. Therefore air permeability will not have such a large influence on the feeling of comfort, since it will be only the inner layer. While working in the "hermetic" protective clothing, skin humidity increases, which can cause the sensation of breathlessness and general discomfort during work. Moreover sweat is accumulated on the skin in a liquid form. High temperature and moisture occurring on the human skin is the reason for heat stress and burden for the human body, which consequently can reduce the ability to work. Better conditions for working in hot places are when more sweat gathered on the skin is transported through underwear to the next layer of the clothing set [12, 13]. In this case, we

Table 2. Comparison of test results for underwear chosen.

	A	B	C	D
Thermal insulation	+	+	+++	-
Water vapour permeability	+	+++	++	+
Air permeability	++	+++	++	-

decided that the best physical properties for the foundry worker will be provided by underwear B because of better water vapour and air permeability. When a foundry worker puts on a protection suit made from aluminised fabric and clothes of flame retardant finishing, underwear B would provide the best water and air permeability, which could help to ensure better-working conditions for personnel in high temperature.

Table 2 shows a comparison of thermal properties of particular types of underwear. Underwear marked with +++ achieved the highest level of parameters of all those measured during this investigation of underwear products. The task of providing physiological comfort at a higher level than it does in current conditions of using protective clothing is a very complex task. The optimal solution, in this case, was to only evaluate results obtained after carrying out the tests mentioned before. In further research it would be useful to elaborate a general comfort quality index for underwear. Further studies into suit construction and of underwear - different kinds of raw material or even different combinations of stitches can show other solutions in such important areas as physiological comfort.

Conclusions

In specific conditions of foundry worker activity the most important parameter describing physiological comfort during work in high temperature is thermal insulation. Underwear C achieves the highest level of thermal insulation, marked as +++. Air permeability and water vapour parameters are less important in this case. However, these parameters achieved good values, marked as ++. Consequently underwear C was chosen as the best for our purposes compared to the other kinds of underwear examined during this investigation.

Acknowledgement

The research was conducted and completed thanks to the kind cooperation of the Brubeck Company. The work was partially funded by Structural Funds within the framework of

a project entitled "Development of a research infrastructure of innovative techniques and technologies for textile clothing" CLO-2IN-TEX, funded by the Operational Programme Innovative Economy - (Action 2.1)

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Received 17.12.2014 Reviewed 29.07.2016