Testing of the thermal properties of composite clothing and clothing

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Review paper

For the successful technical design of composite clothing and clothing, it is necessary to define and test the thermal properties. A review of the literature revealed that a large number of different measuring instruments and measuring systems have been developed for this purpose and numerous studies have been carried out with their help. This paper presents factors that influence the thermal comfort of clothing,, and the measurement units, measuring instruments and systems that are most commonly used for this purpose. In addition, other important research work on the thermal properties of embedding materials, composite clothing and clothing is listed.

Keywords: *thermal properties; clothing composites; clothing; measuring instruments and methods*

Pregled

Za uspješno tehničko projektiranje odjevnih kompozita i odjeće potrebno je definirati i ispitati, između ostalog, toplinska svojstva. Pregledom literature utvrđeno je da je u tu svrhu razvijen velik broj različitih mjernih uređaja i mjernih sustava pomoću kojih su provedena mnogobrojna istraživanja. U radu su prikazani faktori koji utječu na toplinsku ugodu odjeće, mjerne jedinice te mjerni uređaji i sustavi koji se najčešće koriste u tu svrhu, a navedena su i značajnija istraživanja toplinskih svojstava ugradbenih materijala, odjevnih kompozita i odjeće.

Ključne riječi: *toplinska svojstva, odjevni kompoziti, odjeća, mjerni uređaji i metode*

1. Introduction

The technical design of clothing must take into account the influence of the human anatomy and physiological characteristics, the activities and environmental conditions in which the clothing is to be used, as well as the influence of the type of embedding materials and the construction of the assembled clothing. Technical design is very complex, with the most important starting point being the functionality of the clothing and its thermal properties. When considering the parameters that influence the functionality and thermal comfort of a clothing, it is important to take into account the influence of layers that can have a negative impact on the wearer's freedom of movement and the weight of the clothing. In order to objectively evaluate the thermal insulation properties of composite clothing and clothing, measurement systems and methods are used to determine parameters such as the water vapour resistance and thermal resistance of embedded materials and clothing composites, the thermal insulation of clothing, thermal conductivity, temperature gradients, etc. With the development and use of measuring instruments, subjective assessments based on individual experience are replaced by objective investirations.

2. Thermal comfort and factors that influence it

Clothing provides satisfactory thermal insulation when we have achieved a feeling of thermal comfort in it. Thermal comfort is a subjective feeling and is defined according to ISO 7730:2005 as a state of consciousness that expresses satisfaction with the thermal conditions of the environment where there is no need to correct the environmental conditions [1]. Fig.1 shows the exchange of thermal energy between the human body and the environment. Heat transfer takes place until thermal equilibrium is established. The human body produces about 75 W of heat during sleep and 1000 W during strenuous exercise. Excess heat is transferred to the environment by convection and conduction: 12% to the air, 3% to objects, 60% to the environment by radiation from the unclothed human body at room temperature and 25% by evapouration [2-4].

The human thermoregulatory system contributes to the maintenance of thermal equilibrium by constantly balancing the amount of heat produced and the amount of heat lost, with the amount of heat lost being regulated by changes in blood flow (vasoconstriction and vasodilation) [6]. The range of optimal central body temperature is 36.1°C-37.8°C, and the maintenance of central body temperature in this range involves the temperatures of two parallel processes of thermoregulation: behavioral and physiological temperature regulation, Fig. 2 [7, 8]. Behavioral temperature regulation occurs through conscious behavior and can include all appropriate means and procedures aimed at preserving or releasing heat, such as opening windows or wearing extra layers of clothing. Physiological temperature regulation occurs through responses that are not based on conscious and voluntary behavior [7, 9, 10].

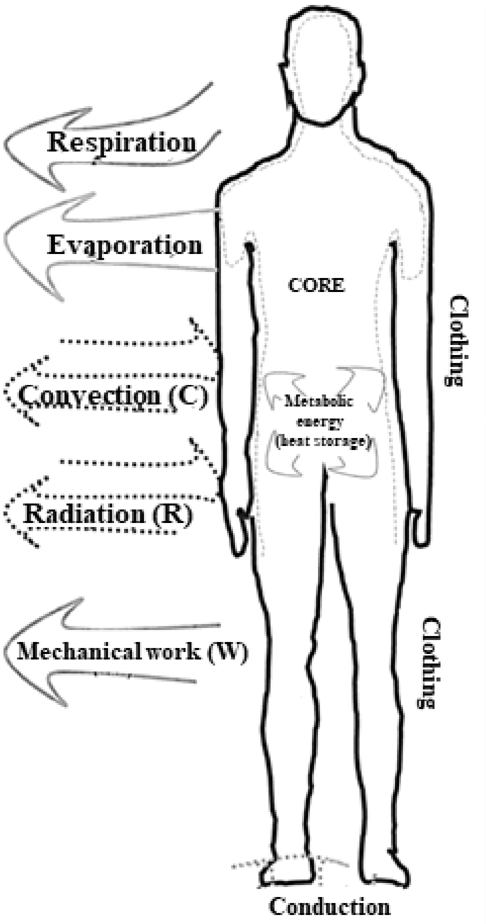


Fig.1 Illustration of heat exchange between the human body and the environment [5]

Thermal comfort is influenced by the human factor, the environmental factor and the clothing factor [3, 11-13]. When considering the influence of human factors, physical activity, gender, age, health status and diet must be taken into account. During physical activity, the human body produces heat and the body temperature rises. The greater the physical activity, the more heat the body produces and it is necessary to reduce the heat so that the body does not overheat and heat stroke does not occur [2, 9, 13, 14].

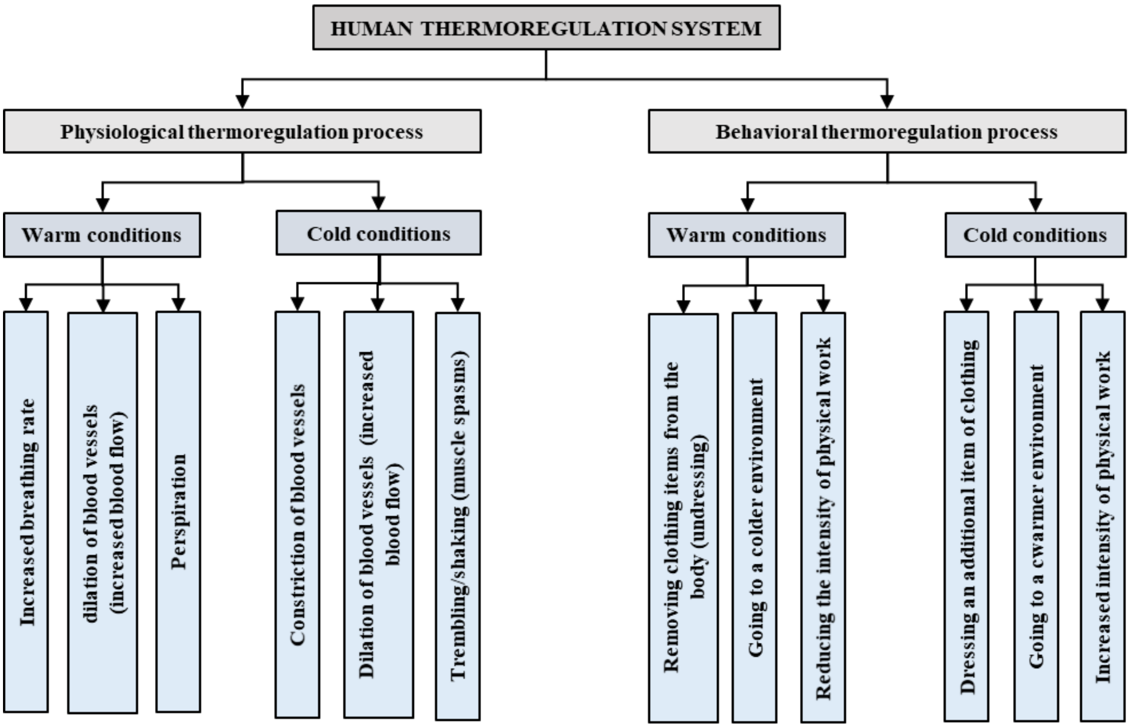


Fig.2 Illustration of the thermoregulation system of the human body [8]

Metabolic heat is the result of the conversion of oxygen and nutrients that a person takes into the body into mechanical energy, which is converted into heat during physical activity. Continuous metabolic heat production and thermoregulatory mechanisms for heat conservation ensure optimal core body temperature in mild cold [9, 14-16]. Metabolic equivalents (Met) are used to define metabolic activity, which represents a person's heat energy at rest, i.e. energy consumption per unit area [16-18].

Air temperature, radiation temperature and surface temperature of objects in the environment influence thermal comfort. The higher the air temperature in the environment, the less heat the human body loses through the processes of convection, conduction and radiation, and the body temperature rises [2, 10]. The speed of the airflow in the environment in which a person is located influences heat loss through convection and evapouration, and as the speed of the airflow increases, heat loss also increases [10, 19].

Clothing ensures the thermal comfort of the wearer in the environment in which they are located. Its influence on the heat exchange between the human body and the environment is of the utmost importance [2, 4, 20-21]. Thermal conductivity is a property of the clothing material that expresses its ability to allow heat to flow, and thermal insulation is the ability of clothing to retain heat [22-24].

Clothing enables a state of psychological, sensory and thermal comfort that depends on the thickness of the embedded material and the type, structure and length of the fibers in which air and thus heat is trapped [25-28]. Fig.3 shows the influence of the thickness of the embedded material on the thermal resistance. It can be clearly seen that as the thickness of the material increases, the thermal resistance also increases.

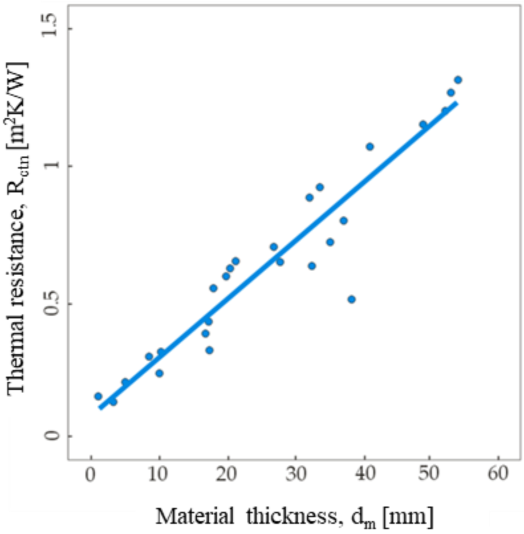


Fig.3 The influence of material thickness on thermal resistance [14]

The thermal properties of clothing are also influenced by different treatments to which the embedded material is subjected, e.g. treatments to produce windproof and water-repellent materials and embedded membranes [15, 2, 21].

3. Units of measurement for determining the thermal insulation of clothing

Before the 1940s, no importance was attached to quantifying the thermal properties of clothing [29]. The first research in this field was carried out for military purposes by A.P. Gagge et al. [30]. They defined units of measurement and numerical methods for determining thermal comfort. A. P. Gagge defined a numerical model for determining the thermal balance of the human body (2-node model) [30]. P.O. Fanger defined indices for thermal comfort, revised Gagge's equation and expressed the energy exchange between the human body and the environment numerically [11]. A. P. Gagge et al. proposed a new unique unit of measurement for thermal insulation, which they called Clo. They established the value in correlation with previous units of measurement, i.e. 1,0 Clo is defined as the thermal insulation of clothing with a value of 0,18 m^2°C/kcal, which corresponds to 0,155 m^2°C/W [30]. For a simpler perception of these units, it should be noted that the unclothed human body has a thermal insulation of 0,0 Clo and the value of 1,0 Clo for thermal insulation represents the amount at which clothing balances heat production and heat loss. This refers to the clothing a person wears (cotton underwear and a typical business suit) and feels thermally comfortable when sitting in a ventilated room, with a metabolic activity of 1,0 Met, an ambient temperature of 21°C, an airflow of 0,1 m/s and a relative humidity of less than 50%.

Tab.1 Thermal insulation of clothing [1, 7]

Clothing	[Clo]	[Tog]
Underpants	0.03	0.05
Long underwear	0.10	0.16
Undershirt	0.04	0.06
T-shirt	0.09	0.14
Shirt with long sleeves	0.12	0.19
Underpants and bra	0.03	0.05
Shirt with short sleeves	0.15	0.23
Flannel shirt	0.30	0.47
Shorts	0.06	0.09
Summer pants	0.20	0.31
Winter pants	0.28	0.43
Summer skirt	0.15	0.23
Winter skirt	0.25	0.39
Light dress, short sleeves	0.20	0.31
Winter dress, long sleeves	0.40	0.62
Vest without sleeves	0.12	0.19
Thin vest	0.20	0.31
Pullover	0.28	0.43
A thick sweater	0.35	0.54
Summer jacket	0.25	0.39
Work jacket	0.30	0.47
Coat	0.60	0.93
Park	0.70	1.09
Socks	0.02	0.03
Thick ankle socks	0.05	0.08
Thick long socks	0.10	0.16
Pantyhose	0.03	0.05
Shoes (thin sole)	0.02	0.03
Shoes (thick sole)	0.04	0.06
Boots	0.10	0.16
Gloves	0.05	0.08

Another unit of measurement for thermal insulation is Tog, which is used to express the value of the thermal properties of embedding materials and clothing [31-32]. It is defined as an alternative to the unit m^{2}K/W and is more commonly used in Europe, while Clo is more common in America [33]. A higher value of the units Tog and Clo indicates better thermal insulation of the clothing [34]. Tab.1 shows the thermal insulation values of clothing, expressed in units of Clo and Tog, and Tab.2 shows the thermal insulation values for clothing combinations.

The metabolic equivalent represents the ratio between a person's metabolic rate at rest and during physical activity. The Met value describes the intensity of activity as energy consumption in a given time, which depends on the person's age, fitness, gender and state of health [35]. 1 Met indicates the amount of oxygen consumed at rest, also known as basal metabolic rate.

Tab.2 Thermal insulation values of clothing combinations

Clothing combination	Thermal insulation	
	[Clo]	[m^{2}K/W]
Underwear (panties), shirt, pants, socks, shoes	0.75	0.12
Underwear (panties), shirt, trousers, jacket, socks, shoes	0.85	0.14
Underwear with long sleeves and legs, thermal jacket, socks, shoes	1.20	0.185
Underwear with short sleeves and pants, shirt, pants, jacket, thermal jacket and pants, socks, shoes	1.55	0.23
Underwear with long sleeves and pants, thermal jacket and pants, parka, socks, shoes, hat, gloves	2.20	0.34
Panties, petticoat, socks, light dress with sleeves, sandals	0.45	0.07
Panties, socks, short-sleeved shirt, skirt, sandals	0.55	0.09
Underpants, tracksuit (sweater and trousers), long socks, tights	0.75	0.12
Briefs, short-sleeved undershirt, shirt, pants, V-neck sweater, socks, shoes	0.95	0.15
Underpants, socks, blouse, long skirt, jacket, shoes	1.10	0.17

In men it is around 250 ml/min and in women around 200 ml/min. The metabolic equivalent is expressed as oxygen consumption per unit of body mass [17, 36]. The maximum oxygen consumption that a person can achieve during physical activity is called VO_{2max} and is expressed in units of mlO_2/kg/min [20, 39, 40].
The known Met value of a physical activity can be used to determine the amount of calories burned during the performance of that activity. Met values can be calculated in accordance with the international standard HRN EN ISO 8996:2021 [37]. Tab.3 shows the Met values for some common activities.

Tab.3 Metabolic equivalent values for some common activities [37]

Physical activity	**Met**	**Wh/m^2**
Activities with a low level of fatigue	< 3	
• Sleep	0.9	52.4
• Watching television	1.0	52.8
• Writing, working at a desk, typing	1.8	104.8
• Walking (2.7 km/h), on a flat surface, easy, very slowly	2.3	133.9
• Walking (4 km/h)	2.9	168.8
Activities with a medium degree of fatigue	3 to 6	
• Riding a bicycle	3.0	174.6
• Walking (4.8 km/h)	3.3	192.1
• Gymnastics exercise (light or moderate effort)	3.5	203.7
• Walking (5.5 km/h)	3.6	209.5
• Riding a bicycle, (<16 km/h)	4.0	232.8
Activities with a high degree of fatigue	> 6	
• Relaxed running at a light to moderate pace (eng. jogging)	7.0	407.4
• Exercise (push-ups, sit-ups, pull-ups)	8.0	465.6
• Running, jogging in place	8.0	465.6

In their article, J. Huang and W. Xu propose a new unit of measurement called Com [38]. According to the authors, consumers can more easily understand the importance of thermal insulation of clothing using the Com unit, as this unit of measurement directly indicates the air temperature at which it is possible to achieve and maintain a sense of thermal comfort when a person is at rest under ambient conditions of 50% relative humidity and an airflow velocity of 0.1 m/s. The lower the value of the Com unit, the more comfortable it is. The lower the value of the Com unit, the more comfortable the clothing is. A lower Com value leads to better thermal insulation of the clothing. They justify the definition of the Com unit by stating that it would make it easier for consumers to perceive the thermal insulation properties of the garment compared to the units m^2K/W, Clo and Met. Tab.4 shows the values of the units Com and Clo as a function of the ambient temperature. Based on the data in the table, the authors conclude that when the air temperature is lowered by about 6 °C, it is necessary to increase the thermal insulation of the clothing by 1.0 Clo in order to achieve a feeling of thermal comfort.

Tab.4 Numerical values of the measuring units Clo and Com in relation to the ambient temperature [38]

Ambient temperature [°C]	**Thermal insulation of clothing**	
	[Clo]	**[Com]**
21.5	1	22
15.6	2	16
9.7	3	10
3.8	4	4
-2.1	5	-2
-8.0	6	-8
-14.0	7	-14
-20.0	8	-20
-26.0	9	-26
-32.0	10	-32

In view of the fact that a theoretical discussion was conducted in the aforementioned work and that no further work on this topic was found after a further review of the literature, it is questionable whether this unit of measurement is still being researched.

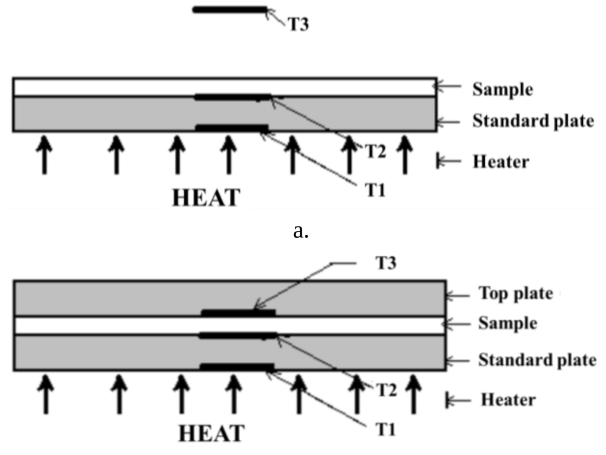
4. Measuring instruments for testing the thermal properties of composite clothing and clothing

Measuring instruments Togmetar, hot plate, Alambeta and thermal manikins are most often used for testing the thermal insulation properties under standardized conditions [12, 39].

4.1. Togmetar

A togmeter is a measuring device used to measure the temperature difference and heat flow through a sample in order to determine its thermal properties. It is used to carry out measurements according to the one-plate method and the two-plate method, Fig.4. The device consists of a thermostatically controlled lower heating plate, which is covered with a reference sample with a known thermal resistance. It also consists of the upper, so-called cooling plates, whose temperature is maintained at the ambient temperature or a temperature higher than the ambient temperature. The temperature is measured on both plates and the plate heater is adjusted to maintain a temperature in the range of 31 to 35°C. Air flows above the device and the ambient conditions under which the tests are performed are an ambient temperature of 22°C ± 2°C and a relative humidity of 65% ± 5% [12, 40, 41]. The air above the test sample has a significant influence on the measurement results, so the togmeter measurement method is a measurement of the thermal resistance of the sample including the air layer next to the measurement surface. For this reason, in both measurement methods, the calibration of the measuring device is carried out to measure the value of the thermal resistance of the air. To determine the thermal resistance of the air, a measurement is made in which the device reaches thermal equilibrium without introducing a sample. When thermal equilibrium is reached, the thermal resistance of the air is determined [12, 40]. To determine the thermal resistance of the sample, the measurement is repeated so that the sample is placed on the base plate and the measuring device reaches thermal equilibrium again.

In the single plate method, Fig.4a, the sample is placed on the lower heated plate, the upper part remains uncovered, and the upper plate is used to measure the air temperature. The single plate method is generally used for material samples that are in direct contact with the environment on the finished clothing.



a.

b.

Fig.4 Measuring instrument Togmeter: a. single plate method; b. two plate method [12]

In the test with the two plate method, Fig. 4b, the test sample is placed on a reference material with a known thermal resistance, which is heated by a thermostatically controlled heated standard plate. The test sample is placed between the top and standard plates at a specific pressure that ensures a uniform thickness of the measuring sample on the measurement surface. The top plate is placed in such a way that the sample is not compressed. Under steady-state conditions, three temperatures are measured: the temperature of the standard plate, the temperature between the upper surface of the reference material (front side) and the lower surface of the measurement sample (back side) and the temperature between the upper surface of the measurement sample and the upper plate T3 [40]. The two-plate method is used for samples of materials that are in a clothing composite or clothing system and are not in direct contact with the environment. The top plate then helps to simulate a closed system, i.e. a material that is not in contact with the environment [40].

4.2. Hot plate

The dry hot plate is used to determine the thermal resistance. It consists of a heated plate, the so-called guard, and the lower plate, Fig.5. The guard plate is a metal plate with a heated plate built into the recess for the test. Its temperature is maintained by a separate heating system that keeps it at a temperature equal to that of the measuring plate. The guard ensures that all the heat generated is conducted evenly through the sample, i.e. that there is no heat dissipation and loss at the sides, which is essential for the accuracy and precision of the measurement results. All three plates have a constant temperature in the range in which the temperature of the skin on the human body moves, i.e. in the range of 33°C to 36°C, which is maintained with the help of heaters located under the measuring surface and which ensure that the heat is only conducted upwards in the direction of the sample thickness [12, 42]. Before the measurement on the sample, a calibration measurement is carried out in which the electrical power required to maintain the set temperature of the measuring plate is measured, i.e. the constant of the hot plate is determined.

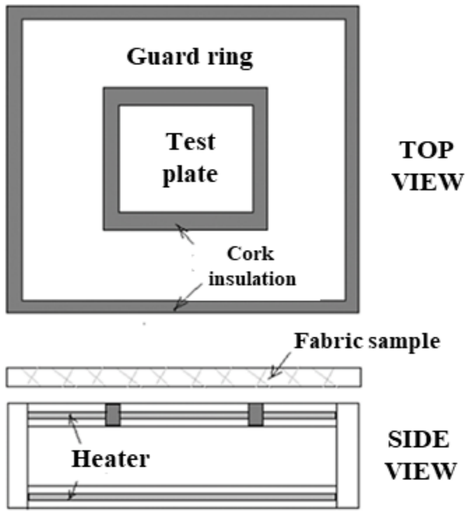


Fig.5 Top and side view of the measuring instrument hot plate with guards [12]

The measuring instrument is started without a set sample to determine the thermal resistance of the empty measurement surface and the air above the measuring surface at a distance of 500 mm above the plate. Before the measurement is carried out on the sample, it must be conditioned to the ambient conditions under which the measurement is to be carried out. After carrying out the calibration measurement, a measurement sample is placed on the measurement surface and the instrument is restarted. The measured thermal resistance is made up of the thermal resistance of the sample and the non-negligible thermal resistance of the air above the material [12, 43].

According to the ASTM D 1518-85 standard, the hot plate measurement method determines the total heat transfer caused by the combined effect of conduction, convection and radiation on textiles and other embedding materials which have a thermal resistance in the range of 0,7 to 14 m^2K/W and whose thickness is not greater than 50 mm [12, 42, 44].

The hot plate method, which can simulate sweating, is identical to the dry hot plate measurement method according to ISO 11092:2014 [45]. The 50,8x50,8 cm sample is conditioned at an ambient temperature of 20°C and a relative humidity of 65% and placed on the perforated surface of a heated plate covered with a PTFE membrane that allows the water vapour to pass through but prevents the sample from being moistened with water. The plate and the membrane simulate the transpiration of the human body. The temperature of the plate is kept constant at 35±0,5°C, with a relative humidity of 40% and an airflow velocity of 1 m/s. The water that flows through the plate and the membrane evapourates. The electrical energy used to maintain the temperature of the plate is a parameter of the water vapour resistance. The water vapour resistance of the sample is determined by measuring the heat loss through evapouration. The duration of the measurement is one to two hours, which is the main disadvantage of this measurement method [12, 43, 46].

4.3. Alambeta

Alambeta is an instrument for measuring the thickness of embedding materials, thermal conductivity, heat diffusion, heat absorption, thermal resistance, the ratio of maximum to steady-state heat flux density and the steady-state heat flux density at the contact point, Fig.6 [12, 47]. The instrument consists of two measuring heads between which the measurement sample is placed. Both measuring heads are equipped with heat flow sensors. The lower measuring head is set to the ambient temperature and the upper, heated head maintains a constant temperature. When the upper measuring head is lowered onto the sample, the heat flow on the top and bottom of the sample can be measured. The basic principle of the measuring is to measure and process the heat flow as a function of time [12, 47].

Fig.6 Alambeta measuring instrument [48]

4.4. An instrument for determining water vapour permeability, the so-called glass method

Evapouration is an important mechanism by which the body loses excess heat. There are two forms of evapouration: in the form of water vapour, which is released from the body to the embedded material and from the embedded material to the environment, and in the form of perspiration [49, 50]. Fig. 7 shows the determination of water vapour permeability using the so-called glass method. Before the actual test, the mass of the sample is weighed.

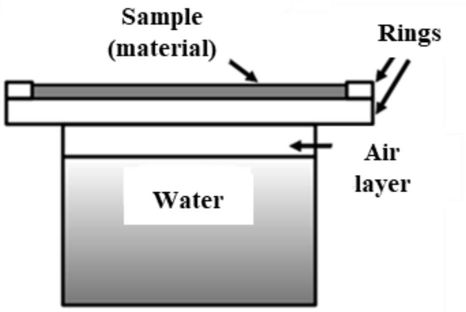


Fig.7 Illustration of the water vapour permeability test using glass method [46]

After the specified time, the mass of the sample is weighed again, which provides information about the amount of water vapour absorbed by the sample. The tests are carried out under standardized conditions and the sample is fixed in a container. Distilled water is placed underneath and there is a 10 mm air space between the water and the sample. The water vapour permeability index is calculated based on the water vapour permeability (WVP) of the sample. The value of the water vapour permeability is the reciprocal of the water vapour resistance, which means that a higher resistance is negative for the wearer [47, 50, 51].

4.5. Permetest

Permetest is an instrument for the non-destructive determination of thermal resistance and water vapour resistance, Fig. 8. Its greatest advantage is the fast and non-destructive measurement method. It consists of a housing with electronic elements and the so-called air tunnel. The round measuring head is attached to the air tunnel and consists of a circular, porous hot plate with a diameter of 8 cm, which can be moved vertically to insert a sample of the material. The measuring instrument was patented by L. Hes from the Technical University of Liberec, Department of Textile Evaluation [52].

Fig.8 Measuring instrument for non-destructive measurment vapour permeability and water vapour resistance - Permetest

The measurement of the water vapour resistance is carried out at an ambient temperature of 20-25°C and a relative humidity of 40-50%.

4.6. Thermal manikins

Thermal manikins, Fig.9, are measurement systems in the shape of the human body that are used to determine the thermal insulation properties of clothing and they differ in their size, shape, number of segments, management method and measuring method. In clothing engineering, precisely determined thermal properties of clothing are used for the technical development of clothing systems [39, 53-54]. In addition to the development of thermal manikins, special measuring instruments are also being developed which simulate the heat transfer on individual body parts depending on the application, e.g. for testing the thermal resistance of shoes, gloves, helmets, etc. The following anatomically shaped measuring instruments can be cited as examples [55]:

- thermal torso for measuring the thermal insulation of clothing, Fig.9a.
- thermal feet for measuring the thermal insulation of footwear, Fig.9b.
- thermal hands for measuring the thermal insulation of gloves, Fig.9c.
- thermal heads for measuring the thermal insulation of different headgear, Fig.9d.

The first thermal manikin was developed in the 1940s in the USA for the needs of the US Army, Fig.10. It was made of copper, consisted of one segment and was used for measurements in static mode. A heat source was responsible for heating the entire manikin and the heat was conducted through the body with the help of a fan. During the development of the manikin and based on the measurement results, it became clear that it had to be able to react to the thermal environment and stimuli like the human body. To achieve this, the technical performance of the manikin had to be improved and made flexible so that it could simulate human movements such as walking, running, climbing, sitting, etc. By increasing the number of segments of thermal manikins, the measurements could be more precise [39, 54, 56]. Plastic and aluminium were used for the production of manikins.

a. b. c. d.

Fig.9 Anatomically shaped measuring instruments for measuring thermal insulation: a. thermal torso; b. thermal foot; c. thermal hand and d. thermal head [58]

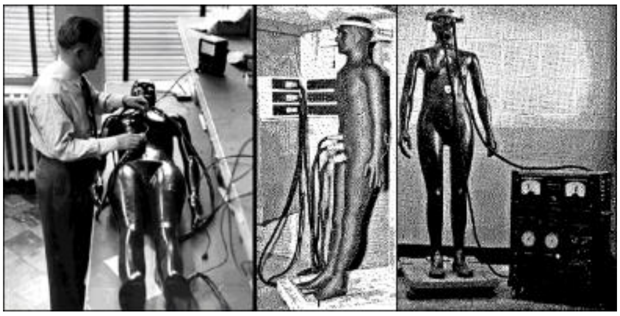
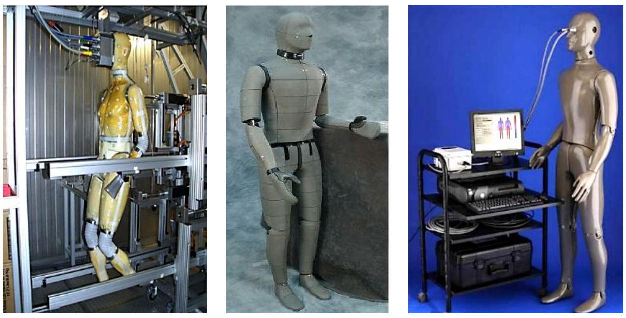


Fig.10 First manikins made entirely of copper [57]

Significant progress in the development of manikins was made possible by the introduction of digital control of the measurement system and measurement methods with improved measurement accuracy. The further development of manikins relates to the ability to simulate sweating, which is essential for maintaining human body temperature. In 1989, the first manikin with an anatomical female body shape was produced. The main reason for the development was that there are potentially more variations in women's clothing, i.e. clothing styles, constructions, materials, layers, etc. Warming manikins with the anatomical shape of a child's body have also been developed to further expand the range of applications for children's clothing. The latest improvement in dolls is the simulation of breathing. All recently produced manikins have at least 15 segments that are thermally independent, such as the head, chest, back, hands, forearms, thighs, upper and lower legs and feet [39, 53, 57].

The thermal manikin Sam (Sweating Agile Thermal Manikin) is a multi-segment, anatomically shaped manikin made of stainless steel and aluminum with movable joints in the hip, knee, shoulder and elbow area, which enables the simulation of human movements such as walking, running, climbing, etc., but also static positions such as standing, sitting, etc., Fig.11a. There are a total of 125 sweating zones on the segments, i.e. a hole through which a liquid flows to simulate sweating [57]. The multi-part Adam manikin is manufactured in America, Fig.11b. All the equipment needed to control the manikin is located in its body (batteries, water tank, power supply, control and data acquisition).



a. b. c.

Fig.11 Thermal manikins: a. Sam, b. Adam, c. Newton [57-59]

Its main purpose is to test the climatic conditions of the environment in cars, airplanes and the like [58]. The Newton thermal manikin is used to test the thermal properties of clothing and sleeping bags (Fig.11c). Thank you to a large number of movable elements (ankles, elbows, knees, hands and hips), it can simulate different human movements [59]. The Nemo manikin is intended for testing equipment and clothing for divers, military suits for marines and other protective clothing, Fig.12a. It is made of aluminum and has 23 segments. The tests are carried out so that the manikin is fully immersed in water to a depth of three meters [60]. The Charlie thermal manikin was developed for testing sleeping bags, Fig.12b. With further improvements, the Charlie 3 manikin was developed, which consists of 16 segments [60].

a. b.

c. d.

Fig.12 Thermal manikins: a. Nemo; b. Charlie; c. Charlene; d. Baby Ruth [55, 60]

Charlene, Fig.12c, is an anatomical thermal manikin with the shape and physical characteristics of a child. It is made of polymer materials and has several segments. It is used to test bedding for children's beds. The eleven segmented manikin, known as Baby Ruth, Fig.12d, was developed to assess the thermal insulation of baby clothing, bedding, car seats, etc. [55].

The Sherlock thermal manikin can simulate sweating, Fig. 13a. It has several segments and can be placed in different positions. It is intended for testing different types of chairs, such as office chairs, car seats, airplane seats, etc. [60].

a. b. c.

Fig.13 Thermal manikins: a. Sherlock; b. Walter; c. Liz [55, 60, 61]

The Walter thermal manikin can simulate sweating, Fig.13b. It differs from other manikins with this option in that it is partly made of fabric, i.e. several layers and a membrane. It also has a built-in system for circulating water throughout the body, which simulates blood circulation in humans and enables the simulation of sweating in all parts of the body with great precision [60]. The Liz thermal manikin, which is anatomically modeled on the female body, was created using a 3D CAD computer modeling system and scans of real people to make the manikin as physiologically similar to the female body as possible, Fig.13c. As the design of this manikin is based on the Newton thermal manikin, Liz can also simulate sweating.

4.7. Integrated measuring system for testing the thermal properties of composite clothing and clothing

The University of Zagreb Faculty of Textile Technology has installed an integrated measuring system for testing the thermal properties of composite clothing and clothing. The measuring system consists of a instrument for testing air permeability, a Permetest, a hot plate, a thermal manikin, a multi-purpose differrential conductometer, a instrument for testing differential temperature gradients and a instrument for measuring the physiological parameters of the human body for an accurate evaluation of the thermal comfort of clothing. The aforementioned measuring system has already been described in detail in the journal *Tekstil* [62].

5. Previous research on the thermal properties of composite clothing and clothing

Scientists and other experts in the field of clothing engineering carry out tests on the thermal properties of embedding materials, composite clothing and clothing using different measuring instruments based on stipulated standards.

M. Matusiak investigates the relationship between the thermal properties of composite clothing and their individual layers used for winter clothing using the Alambeta measuring instrument [63]. The results confirm the author's assumptions that the thermal properties of composite clothing depend on the configuration of the individual layers, and the author concludes that it is possible to roughly define the properties of a clothing composite based on the properties of the individual material layers. In another paper, G. Kosiuk and M. Matusiak investigate the influence of the number of material layers in a clothing composite on its thermal resistance [64]. The measurements were carried out using the Permetest measuring instrument and the results confirmed the authors assumption that the thermal resistance increases as the number of material layers of which the clothing composite consists increases. A. Das et al. investigated the influence of different types of heat transfer on the thermal resistance [65]. The measurements were carried out on a hot plate on five composite clothing with different combinations of layers of embedded materials. According to the authors, the thermal resistance of composite clothing increases with increasing thickness of the trapped air layer between the material layers, and the thermal resistance of all composite clothing is highest for the type of heat transfer without convection at any thickness of the air layer. P. Lizak et al. investigated the influence of the knitted structure of the material made of polypropylene fibers on heat transfer, which was measured experimentally on six samples of the material, each sample being tested with three measuring instruments: Alambeta, Togmetar and the PSM2 measuring instrument [66]. According to the authors, the results showed that the dependence between the observed properties and thermal resistance is not high and that the Alambeta instrument is the most objective method for measuring the thermal parameters of knitted materials due to the speed of measuring and reproducibility of the results. Similar studies are carried out by D. Kopitar et al. who investigate the influence of the mechanical treatment of the material by calendering (calendering) on the structure of the nonwoven polypropylene material and the thermal resistance [67]. F. Z. H. Tabarestani et al. use an objective and subjective method to investigate the influence of the embedded material used as a thermal insulator in the clothing composite for the production of gloves for cold protection on its thermal resistance [68]. Applying a layer of thermal insulator increased the thermal resistance of the gloves due to the increase in the thickness of the clothing composite and the volume of the air layer trapped between the layers of material. According to the authors, an increase in airflow velocity also increases heat loss by convection, and there is a high correlation between objective and subjective test results. D. Atalie et al. investigated the influence of weft yarn twist level on the thermal conductivity of woven cotton material [69]. The measurements showed that increasing weft yarn twist level also increases the thermal conductivity of the material, which means that the thermal resistance decreases. S. Mohapatra et al. investigate the thermal conductivity of polyester materials [70]. The authors observe the influence of the material structure on the thermal conductivity and conclude that it significantly influences the thermal conductivity. Z. E. Kanat conducted with similar investigations [71].

Some authors investigate the influence of the structure and the type of material, and the surface treatments of the material on the thermal conductivity and thermal absorption properties with the aim of defining the feeling of comfort of the material in terms of warm/cold feeling when in contact with the human body [71-75]. In some papers, the authors ignore the thickness of the material, which has a very significant influence on the thermal properties. In a similar study, L. Hes investigated the properties of thermal conductivity, thermal resistance and tactile sensation using 15 artificial furs and 16 animal furs which come into contact with the body [76]. Alambeta and Permetest measuring instruments were used for the measurements. The author concluded that artificial furs have a lower thermal resistance but give a better feeling of warmth when they come into contact with the body. When comparing the water vapour permeability between natural and artificial furs, natural furs have a lower permeability of 5% on average, but the author believes that their thermal properties are still very good due to another advantage, namely high moisture absorption. The compressibility of the material plays an important role in the transfer of heat from the human body to the clothing, and in the properties of the finished clothing. The thermal conductivity of a material depends on its ability to absorb heat, i.e. thermal absorption, which is considered to be the tactile sensation of hot/cold upon contact. A. Begum and V. Subramanjam investigated the compressibility of knitted fabrics produced in plain weft knit and with different loop lengths [77]. According to the authors, the compressibility of the material is influenced by the loop length and the density of the knitted fabric. D. Alimaa et al. conducted similar studies on materials made of cashmere fibers and textured polyester materials [78]. According to the authors, the compressibility of the material is affected by the structure of the material, i.e. its mass, the type of fibers it is made of and the loop length. A. Asayesh et al. conducted a similar study in which they investigated the influence of the weave type and the density of the weft on the compressibility of the material [79]. K. A. Asanovic et al. investigated the compressibility of woven materials [80]. According to the authors, materials with a raw material composition of a blend of cotton and polyester in twill weave showed the best compression properties and materials with a raw material composition of cotton in plain weave showed the worst compression properties. A similar study was conducted by J. O. Ukponmwan, who also investigated the effects of wear under wet and humid conditions on the behavior of the materials during compression [34]. Due to their wide application, many authors investigate the compressibility of the so-called spacer material [81-83]. In their work, they investigate the influence of the structure, thickness, layering of the clothing composite, which includes the spacer material, seams and stitching, and other parameters on compressibility. In all studies, the authors come to the conclusion that the parameters mentioned have a pronounced influence on the compressibility of the spacer material.

A small number of authors have investigated differential temperature gradients in clothing, which provide a detailed insight into the influence of the individual layers of the embedding materials of which the clothing composite is made of. W. E. Mell and J. Lawson conducted a study on a numerical model of heat conduction through embedded materials intended for the production of protective clothing for firefighters [84]. The clothing consisted of an outer layer, i.e. a layer of the outer shell, and two inner layers. The first layer towards the body is the so-called thermal layer, and between it and the outer shell there was a third layer of permeable material. There were air pockets between the layers. The predictions of the temperature gradient (temperature drop) between the inner layers of the clothing system by the numerical model deviated by ±5°C from the results of the experimental measurement. When predicting the temperature gradient between the outer conditions and the air pockets after the outer shell, the numerical model obtained temperatures that were up to 24°C higher than the temperatures determined by experimental measurements. Although the authors concluded that these investigations are were very successful it is questionable whether the results obtained with the numerical model and the experimental measurement with such large differences can really be considered successful. The authors do not specify the conditions under which they carried out the experimental measurements, i.e. which parameters they used in the numerical model. Similarly, D. Miedzińska uses a numerical method to investigate the influence of air layers located in the material structure between the layers of a clothing composite intended for the production of protective clothing for firefighters on the temperature distribution through the layers [85]. The paper presents a comparison of the distribution of the differential temperature gradients of a measuring sample of a clothing composite. The measurements showed a visible influence of changes in the shape of the air chambers and an increase in the thickness of the air chambers on the increase in the temperature gradients. M. Schmid et al. conducted similar investigations [86]. The influence of the thickness of the air layers on the thermal resistance of single-layer and double-layer materials is also investigated by D. Gupta et al [87]. The measurements are carried out with the Alambeta, Permetest (manufacturer Sensora) and FX 3300 (manufacturer Testex) measuring instruments for measuring the air permeability of embedding materials and clothing composites. However, the authors do not display differential temperature gradients. According to the authors, the thermal resistance increases significantly with the addition of a material layer to the clothing composite and with an increase in the air layer between the material layers and it can be changed by regulating the air layers between the material layers. Y. Sun et al. conducted a similar study, but using numerical models [88]. In their study, E. Onofrei et al. present numerical predictions of the temperature distribution in the material as a function of time [89]. They conducted research on materials used for the production of heat-protective clothing and on composite clothing consisting of three layers of material. The thickness of the individual layers was determined and a dry hot plate was used. M. Venkataraman et al. find that the thermal conductivity of materials is approximately constant and inversely proportional to their thickness [90]. The authors note that the thermal resistance also increases with increasing thickness of the material and the number of layers and due to the larger amount of trapped air. N. Pan investigates heat loss as a function of the temperature of the environment [22]. He states that the human body acts as an internal heat source in the clothing system and creates a differential temperature gradient between the internal microclimate of the clothing and the environment. Depending on the temperature of the environment, which can be higher, lower or equal to the body temperature, the sign of the differential temperature gradient changes. J-Y. Xu et al. investigated the effect of multilayer protective clothing which consists of an outer layer, a heat-retaining layer, a PCM layer and an outer shell on thermal comfort, with the PCM layer and the heat-retaining layer swapping places [91]. The differential temperature gradients between the body of the subject's body, the multilayer protective clothing and the environment are analyzed as a function of the weather. Based on the determined temperature gradients, it was shown that the PCM layer mainly absorbs the heat of the environment, but also the heat of the human body, which increases thermal comfort. B. Yu et al. also investigate the influence of the thickness of the individual clothing layers on the thermal properties, but do not show differential temperature gradients between the layers, but the overall temperature drop depending on the time of measurement [92]. V. Dupade et al. investigate the influence of the position of the individual material layers in the clothing composite on the thermal resistance at ambient temperatures falling below 0°C [93]. The authors tested two composite clothing on a hot plate, one of which is two-layered and one of which is three-layered and both are made of nonwovens. According to the authors, the thermal resistance of the nonwoven clothing composite increases with increasing ambient temperature, and it was also found that the thermal conductivity of the individual layers of the material decreases in the direction from the body to the environment. The authors also state that the heat flow and thermal resistance of the individual layers of material are not affected by their position in the clothing composite when heat transfer by convection is extremely low.

Many authors focus on the influence of clothing on a person's thermal and physiological comfort under different environmental conditions, but do not investigate the influence of the differential temperature gradients between the individual layers of the clothing system [94]. Thermal comfort is also significantly affected by properties related to moisture transport. This paper lists some significant studies that deal with the investigation of moisture transfer in materials and clothing. L. Hes stands out in the field of research of the influence of water vapour on the thermal comfort of clothing. For many years, he has been working on measuring methods and the construction of instruments that enable precise measurement of the properties associated with moisture transfer [41, 95]. He developed and patented a instrument for measuring the thermal properties of the material Alambeta. He also developed and patented the Permetest for measuring thermal and water vapour resistance. L. Hes et al. are mainly concerned with investigating the thermal properties of materials and clothing and the properties associated with moisture transfer. They have also shown that it is possible to measure the water vapour permeability of polymer films of different thicknesses using the Permetest measuring instrument,, and to evaluate the cooling properties of wet materials [96-98]. MK Imrith et al. also investigate the influence of the thickness, but also the porosity of the material on the thermal properties of materials and clothing composites, using the Alambeta and Permetest measuring instruments [99]. I. Salopek Čubrić et al. investigate the changes in water vapour resistance, mass and thickness of materials with a special polyurethane end coating after being exposed to weather conditions for three months in summer and winter [100]. The authors conclude that the mass and thickness of the material influence the water vapour resistance values. After the material was exposed to summer weather conditions, the water vapour resistance decreased by 11,4% and the thickness by 3,2%. After the material was exposed to winter conditions, the water vapour resistance decreased by 16,7% and the thickness by 3,16%. A. Razzaque et al. also conducted studies on the influence of surface treatment of laminated materials and water vapour resistance [101, 102]. J. Arabuli et al. investigated the water vapour permeability and resistance properties of bovine hides intended for the production of professional footwear [50]. The results show that with similar treatment, the suede sample with smaller thickness has a lower water vapour resistance than the suede sample with larger thickness and that the water vapour permeability depends on the treatment of the upper surface of the tested leather. Similar studies were conducted by J. Akalović et al. and Z. Skenderi et al [103, 104].

Some authors carry out more complex investigations in which they investigate both thermal resistance and water vapour resistance. A group of authors from the University of Zagreb at the Faculty of Textile Technology investigate the influence of the construction characteristics of yarns and materials, and laminated materials on thermal resistance and water vapour resistance [105-108]. They also investigate the change in the resistance of materials in terms of water vapour resistance and thermal resistance when exposed to real climatic conditions in winter and summer [110-111]. The so-called dry hot plate and hot plate with sweating simulation were used. In most of the mentioned studies, the water vapour resistance and thermal resistance of yarns or materials under certain environmental conditions for work, sports, special or conventional clothing are investigated. Based on the results of the mentioned studies, the authors conclude that the construction parameters of the material have a significant impact on the water vapour resistance,, and the final treatments of the material and the air trapped in the structure of the material on the reduction of thermal resistance. They also conclude that the differences in thermal resistance between the materials in finished clothing are not large and that the layering of the material leads to an average increase in thermal resistance of 143%, and an increase in the mass of the material. L. Hes et al. also investigate the influence of the construction characteristics of materials on their thermal resistance and their properties in relation to the transfer of water vapour [112-114]. Based on the results, the authors conclude that with increasing moisture in the material and under real use conditions, thermal comfort decreases significantly compared to measurements on dry samples and that the mass and composition of the material influence the thermal properties of clothing composites. According to the authors, heat transfer by conduction and heat absorption increase when the material is wet, and there is a direct mutual influence between the amount of moisture in the material and the water vapour permeability, and the physiological properties of the material. L. Hes and M. de Arujo also investigate the water vapour permeability of wet cotton materials and the influence of air layers between the skin and the material on the total relative heat flow (eng. cooling effect) [115]. And in his work, H. Özdemir determines the thermal resistance and water vapour resistance for materials commonly used in the manufacture of clothing [116]. The results show that materials with different raw material compositions and different proportions, in this case polyester and cotton, have different thermal resistance and water vapour resistance. According to the authors, the material that is the best isolator, i.e. has the greatest thermal resistance, is a material with a raw material composition of 65% polyester and 35% cotton. The authors also conclude that the material with the highest water vapour permeability, i.e. the lowest water vapour resistance, is the one with a raw material composition of 33% polyester and 67% cotton. MB Sampath et al. investigate the influence of material finishes on the thermal insulation properties of knitted materials with different raw material compositions and ratios [117]. The measurements have shown that the finishing of the material has a significant influence on the thermal insulation properties, as it increases the thermal conductivity and heat absorption, and the water vapour resistance.

B. B. Yilma and B. Mijović et al. conduct similar research in which they investigate the influence of the thermal properties of materials and their finishing on the overall transfer of heat and water vapour [118-119]. J. Fan and H. Wu consider the combinations of battings with different properties in two composite clothing and their influence on the thermal and water vapour resistance of the composite clothing [120]. According to the authors, the study showed that the influence of the position of the batting in the clothing composite is significant for practical implementation and that it is possible to optimize the performance of the clothing by using the same materials but placing them in different positions. G. Kosiuk and M.

Matusiak use the Alambeta and Permetest [121] measuring instruments to investigate the influence of quilting in quilted materials, such as those used for quilts, on thermal and water vapour resistance. Based on the results, the authors conclude that the size of the square stitches, the type of stitching and the thickness of the thread and needle used for sewing affect the thermal resistance, and that the samples sewn with a zigzag stitch show better results when measuring the water vapour resistance. L. Hes et al. investigated the influence of incorporating individual layers of material into the clothing composite used for men's business suits on thermal and water vapour resistance [52]. The measurements showed that the thermal resistance of the clothing composite is not equal to the sum of the thermal resistances of the individual layers of materials that make up the clothing composite, but has smaller values. The water vapour resistance of the clothing composite is relatively equal to the sum of the water vapour resistance values of the individual layers. A similar study was conducted by R. A. Angelova et al [122]. In his work, S. H. Eryuruk investigated the influence of composite clothing and their different combinations on the thermal properties of composite clothing [123]. The measurements showed that different layers in the clothing composite, and different combinations of composite clothing significantly influence the thermal properties of the material. The author concludes that the thermal conductivity of the material used as thermal protection and the material used as the outer shell significantly affects the thermal conductivity of the clothing composite. The author also concludes that as the thickness of the clothing composite increases, its thermal and water vapour resistance also increases. Similar studies were carried out by B. Sentil Kumar and T. Murugan [124].

In order to successfully predict the thermal insulation properties of clothing, the results of research of the thermal properties of individual embedding materials and composite clothing must be combined in a meaningful way with research of the thermal properties of the clothing made from them. Many authors study the thermal properties of protective clothing for extremely cold weather conditions and warmer climates [125-126]. In cold conditions, it is interesting to note that clothing must limit and prevent heat transfer from the human body to the environment and provide protection from wind without restricting or reducing the wearer's freedom of movement. It is also important to ensure thermal comfort by layering while increasing the mass of the clothing or clothing system as little as possible. In warmer climates, other thermal properties of materials and clothing are required. A high thermal conductivity of the material is required to ensure that body heat is quickly transferred to the environment, i.e. the lowest possible thermal resistance of the material and the lowest possible thermal insulation of the clothing are required [127-129]. It is very important that moisture is quickly transferred from the human body to the material and from the material to the environment. M. Matusiak and W. Sybilska have analyzed the relationship between the thermal resistance of materials and the thermal insulation of finished clothing [130]. The tests were carried out with Alambeta and a female thermal manikin. According to the authors, the results showed a strong correlation between the thermal resistance of the material and the thermal insulation of the finished clothing, with the results of the measurement on the Alambeta being much lower than the results of the measurement on the thermal manikin, which the authors explain by the occurrence of two layers of air during the test on the manikin: between the manikin and the clothes and the outer layer of air next to the surface of the clothing. M. Konarska et al conducted research on three clothing systems intended for use in very cold weather conditions [131]. The paper does not mention the basic properties of the materials from which the clothing is made. The results show that as the speed of the airflow in the climatic chamber increases, the thermal insulation also decreases and that the method of controlling the transmission of electricity for heating the manikin does not have a major influence. Similar studies are carried out by J. Fan and J. H. Keighley and Y. Key et al [132]. M. Konarska et al. also investigated the subjective perception of thermal comfort. They investigated three clothing systems intended for one-time use in medicine by objective measurements on a thermal manikin and by a subjective method [133]. X-Q. Dai and G. Havenith conducted a study in which they investigated the influence of the air permeability properties and water vapour resistance of the materials used to make jackets on ventilation and heat and moisture transport [134]. A Newton thermal manikin was used and different airflow velocities were set during the measurement, with the thermal manikin being static or in motion. The results showed that already at the beginning of body movement and air movement, ventilation increases, which had a great impact on the water vapour resistance but not on the thermal insulation of the clothing systems. The influence of perspiration on the thermal insulation of clothing is significant, so in the paper by J. Fan et al. a test was carried out on 12 clothing systems using a thermal manikin that simulates sweating at different levels [135]. The study does not contain any detailed information on the materials used. From the results, the authors conclude that the thermal insulation of clothing decreases by 2-8% during sweating and that this decrease is related to the accumulation of water within the clothing system. F. Fung et al. also investigated water vapour resistance. They measured the water vapour resistance on the Permetest and Tora manikin and proved that by measuring the water vapour resistance of materials, it is possible to predict the water vapour resistance of the finished clothing [136]. B. Holland investigates the thermal insulation of seven different sleeping bags and the subjective perception of thermal comfort under the same conditions [137]. The study is carried out on a female thermal manikin and the paper does not specify the properties of the materials from which the sleeping bags are made. A comparison of the results shows that the results obtained are identical, and the author explains the lower values obtained by the subjective assessment of the user with the subjective feeling that occurs when the so-called cold spots, e.g. cold feet, appear. A similar study was carried out by K. Jussila et al. who carried out an objective and subjective study of the thermal insulation of protective clothing for miners in Finland, Sweden, Norway and Russia [138]. The aim of the study conducted by A. V. M. Oliveira et al. was to determine the thermal insulation of nine clothing systems in static and dynamic measurement mode on the female thermal manikin Maria and to compare the results obtained [139]. The results showed that the values obtained by measuring in dynamic mode are always lower than the values obtained by measuring in static mode. In another paper, A. V. M. Oliveira et al. deal with a comparative analysis of methods for measuring the thermal insulation of clothing with a thermal manikin, considering serial, parallel and global measurement methods on 30 items of clothing and nine clothing systems [140]. The results show that the serial method always provides the highest values for thermal insulation and that the global method is the only one that is suitable for all manikin control models.

5.1. Testing of the thermal properties of composite clothing and clothing in the Laboratory for thermal insulation properties of clothing

In the Laboratory for thermal insulation properties of clothing at the Department of Clothing Technology at the University of Zagreb Faculty of Textile Technology, under the leadership of D. Rogale, several measuring instruments have been implemented, some of which have been patented [141-144].

Research of the thermal properties of composite clothing and clothing has been carried out as part of scientific and technological projects that have resulted in numerous scientific papers.

The studies on the thermal manikin were carried out as part of three doctoral theses supervised by D. Rogale [31, 145, 146]. G. Čubrić investigated the thermal properties of chambers embedded in intelligent clothing with adaptive thermal insulation properties [145, 147]. The thermal properties of a intelligent clothing with active thermal protection together with the outer shell were also investigated. The measurements were carried out with active and inactive thermal insulation chambers, in static and dynamic measurement mode. In his doctoral thesis, G. Majstorović deals with the study of the thermal insulation of the outer shell, thermal inserts and clothing systems of special and intelligent clothing,, and multilayer thermal inserts built into special clothing for use in cold conditions [31, 147-152].

I. Špelić conducts objective research on the above-mentioned thermal manikin, and subjective research on the influence of design parameters (construction allowance of the garment commotion and length of the garment) on the thermal properties of men's jackets and studies on the subjective perception of thermal comfort [146, 153-155].

Simultaneous measurements were carried out to determine the thermal resistance through one or more layers of composite clothing and the temperature gradients of the composite layers [32],, and studies on the thermal resistance of different combinations of men's clothing [156] and the measurement of thermal conductivity as a function of compressibility [157]. As part of his doctoral thesis, N. Jukl is investigating the influence of the type of embedding materials used and the construction of composite clothing on the overall thermal properties of clothing.

6. Conclusion

Testing the thermal properties of embedding materials, composite clothing and clothing is a complex process that involves a whole range of thermal parameters. By observing one or more thermal property parameters, it is not possible to successfully predict the thermal properties of clothing. Although there are a large number of developed measuring instruments and methods, there is still a need to improve the existing ones and develop new measuring instruments that combine the complex parameters of the thermal properties of composite clothing and clothing. A large amount of research has already been carried out so far, but it has become apparent that there is a need to standardise measurement methods and instruments that, when used together, will enable a better understanding of the thermal properties of composite clothing and clothing, which will also enable more successful and accurate technical design and development of new clothing according to consumer requirements.

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