Szent István University

Applicability of the Thermal Manikin for Thermal Comfort Investigations

Thesis of PhD Work

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CONTENTS

1. BACKGROUND OF THE TOPIC, GOALS

People always have dealt with their heat sensation as it was cold, then added another piece of clothing or increased the intensity of their activity. The development of the technology and the application of modern knowledge resulted that the thermal comfort studies got scientific character and background.

People live 85-90% of their life in an enclosed place, therefore essential that the enclosed place, designed by the architect, provides those comfort conditions which cause people feel good and ensure people's optimal performance in their physical and mental work.

The comfort theory has been among the priority areas of scientific research in the last few decades. It has been proved, that the physical parameters of the indoor spaces (air temperature, humidity, air velocity, temperature of the surrounding surfaces) affect our activity which we do in enclosed spaces, and our physical and mental working ability. From the 1970's the thermal comfort researches have gotten new approach, when Professor P.O. Fanger developed the complex theoretical and measurement bases for the subjective evaluation of human thermal sensation, in the Technical University of Denmark.

I was lucky, because in the year 1993, I worked together with Professor Fanger for a half year, when we evaluated and processed datas of different thermal sensation examinations. At my previous workplace at the Techniacal University of Budapest, Department of Buiding Service Engineering, in the leadership of Professor Bánhidi I took part in a thermal comfort research work, where we examined the combined effect of the temperature, the noise and the lighting, and how these parameters affect the productivity of mental work. At my current workplace, University of Pécs, Department of Buiding Service Engineering, after the renovation and modernization of the laboratory we had the opportunity to do thermal comfort researches.

Usually the thermal comfort examinations are made with human subjects, but these examinations have high cost and need much more time, because of the many variable parameters. The dissertation examines another option, the measurement with thermal manikin. Originally the thermal manikins were developed to the U.S. Army for testing the military clothing, but later the thermal manikins have been used also for thermal comfort researches. With the usage of the thermal manikin we had better opportunity for doing additional comfort theoretical examinations and human medical applications instead of subjective judgement.

For my research I used the thermal manikin which was made in Hungarian Institute for Building Science, this is the only one thermal manikin in Hungary. First, in the laboratory of the University of Pécs, Department of Buiding Service Engineering, the thermal manikin got military clothing which was worn by the 2. Hungarian Army, at the River Don, in 1943. The result of the thermal sensation research was appeared in several HVAC literature (Bánhidi et al. 2010, Magyar et al. 2011) and military technical literature (Révai et al. 2011a, 2011b, 2012), there were articles in the daily press, a notice was issued by MTI, and there were interviews in the TV and in the radio. During this research and after it I examined the applicability of the thermal manikin.

I assumed that thermal comfort examinations can be carried out using thermal manikin instead of living human subjects. I examined the applicability of the thermal manikin in some typical situation in HVAC field, which not yet worked out. I made examinations that show the further applicability of thermal manikin for thermal comfort examinations.

I assumed that the thermal insulation of clothing should be measured not in itself, but with thermal manikin. The thermal insulation of different clothing can be determined by using the thermal manikin. Several researchers have dealt with the determination of thermal insulation of clothing, and different calculation methods have been developed, but they have not been studied how the results depend on the temperature, therefore my aim was to examine that.

My aim was to determine the heat loss of the whole human body and the different body parts under different ambient temperatures, and different clothing, with the usage of thermal manikin. The knowledge of the heat loss provides important information not only for the comfort theory but for the medical science too.

In the dissertation I examined how the thermal comfort requirements meet the needs within the people-building-comfort-energy contex (Magyar et al. 2002, Magyar 2004, 2005, 2006a, 2006b, 2010). The human heat sensation depends on the air temperature, the relative humidity, the velocity, the average radiant temperature of the surround surfaces, and the activity and the clothing. The aim of my dissertation to make examinations in connection with the clothing, the air temperature and the average radiant temperature of the surround surfaces, from the above mentioned parameters.

In the indoor spaces which designed by the architect, people are often exposed to the effect of the surfaces which have different temperature; this is the radiant temperature asymmetry in the comfort theory. My aim was to examine the combined effect of a cool wall (it can be an external boundary glass wall) and a warm ceiling (e.g. ceiling heating), with usage of thermal manikin.

At the radiant asymmetry, the known calculation method not expresses the combined effect of warm and cool surfaces (the current calculation method applies only to the cool wall or only to the warm ceiling). I assumed that using a thermal manikin, the complex effect of the radiant temperature asymmetry can be examined, e.g. the combined effect of a cool wall (or glass) and a warm ceiling (ceiling heating). My aim was to examine the heat sensation of the people as a function of the distance from the cool window-surface, in different clothing, in a given indoor space.

2. MATERIALS AND METHOD

I developed a modelling concept for my research, I set up a hypotheses.

I examined the applicability of the thermal manikin in thermal comfort measurements. Under identical conditions, I measured the surface temperature of the thermal manikin and the human subjects, with a thermovision camera. The surface temperatures were between 20°C and 30°C, under different operative temperatures. The requirements of the accuracy of the model that the mean surface temperatures must be kept within ± 0,5 °C. This accuracy is sufficient to apply thermal manikin in thermal comfort measurements rather than the human subjects.

I presented the using of the thermal manikin on some field of the comfort theory, which not yet examined. I examined these applications:

- The changes of thermal insulation of clothing depending on the surrounding air temperature.
- The heat loss of the whole human body and different bodyparts depending on different equivalent temperatures.
- Radiant temperature asymmetry: examination of the combined effect of warm ceiling and cool wall/windows.

2.1. Basics and contexts of comfort theory used for the research

The operative temperature is the typical features of the indoor environment. The operative temperature is the heat transfer coefficient weighted average of the air temperature and the mean radiant temperature of the surrounding surfaces.

$$t_o = \frac{\alpha_s \cdot t_{ks} + \alpha_c \cdot t_a}{\alpha_s + \alpha_c} \tag{2.1.}$$

where:

t_o: operative temperature, °C
t_{ks}: mean radiant temperature, °C
t_a: air temperature, °C
α_c: convective heat transfer coefficient, $W/m^2 °C$
α_s: radiant heat transfer coefficient, $W/m^2 °C$

The equivalent temperature is important at the thermal comfort measurements made with thermal manikin. The equivalent temperature is the temperature of an imaginary enclosure with the mean radiant temperature equal to air temperature, no air movement and the person has the same heat exchange by convection and radiation as in the actual conditions.

The thermal comfort can be expressed with PMV-PPD indexes (MSZ EN ISO 7730 (2006), MSZ CR 1752 (2000), MSZ EN 15251 (2008), Ashrae 55 (2010)). Fanger collected subjective sensory thermal data from many persons and developed his theory. The PMV is the predicted mean vote, in the definition, the value of PMV = 0 corresponds to the case when the heat balance equation results are 0, the heat production and heat loss is balanced. On the 7-point thermal sensation scale, at the positive PMV values, the heat production is larger than heat loss, therefore the person feels indoors hot, and at the negative values the examined person is cold. The predicted percentage of disatisfied (PPD) can be expressed depending on the predicted mean vote (PMV). This shows the Figure 2.1.

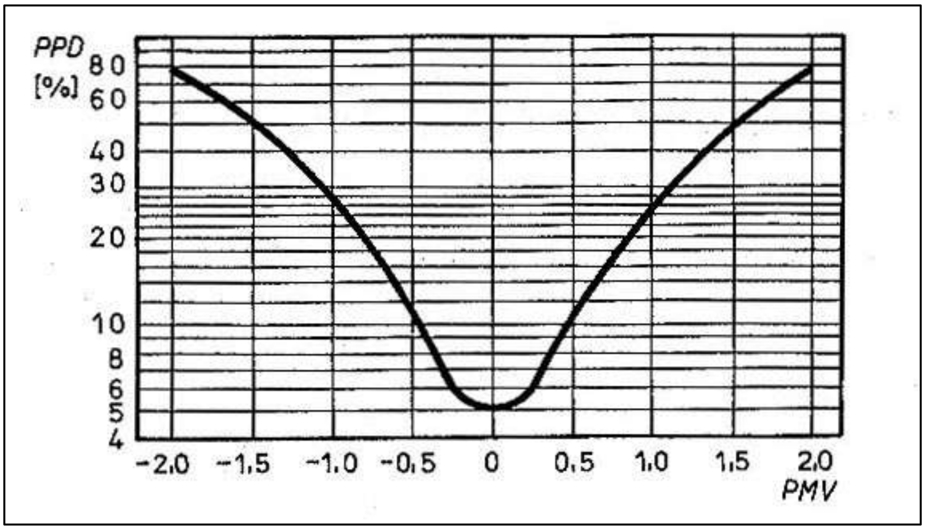

Figure 2.1.
The function of PMV and PPD values

The PMV value curve is symmetrical, and it has a minimum value at 5%, therefore there is not an indoor condition, which satisfied more than 95% of the occupants.

The local thermal comfort is influenced by the radiant temperature asymmetry significantly. The difference in the surface temperature of the surrounding environment causes the radiant temperature asymmetry. The required value of the radiant temperature asymmetry is in the ASHRAE Handbook (2009) and in the MSZ CR 1752 (2000) standards and we can see it in the Table 2.1. and in the Figure 2.2.

Table 2.1.
Required value of the radiant temperature asyimmetry for the three categories of the thermal environment

Category	Radiant temperature asymmetry, °C			
	Warm ceiling	Cool wall	Cool ceiling	Warm wall
A	<5	<10	<14	<23
B	<5	<10	<14	<23
C	<7	<13	<18	<35

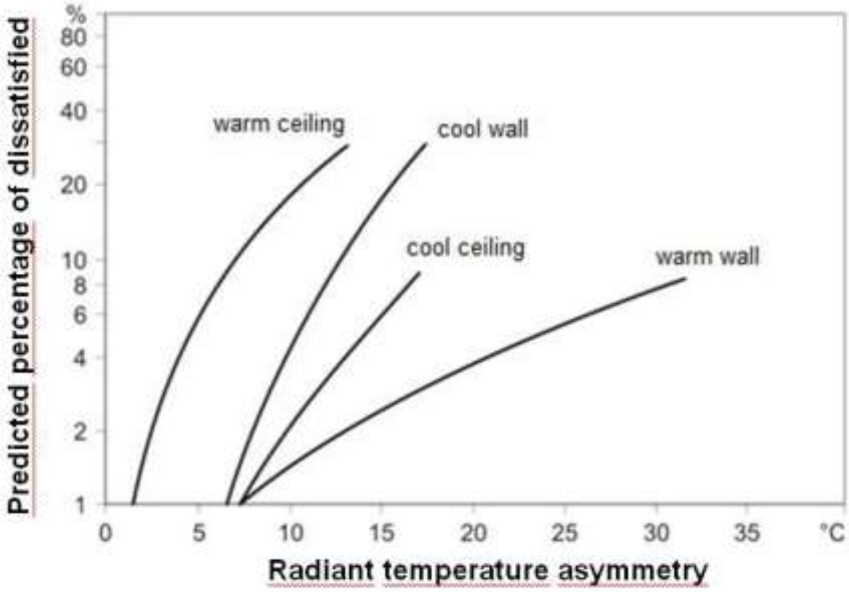

Figure 2.2.

Local discomfort caused by radiant temperature asymmetry

In the Figure 2.2. the predicted percentage of dissatisfied is shown as a function of the radiant temperature asymmetry caused by a warm ceiling, a cool wall, a cool ceiling or by a warm wall. But in practice we can see some cases, when the factors causes the radiant temperature asymmetry occur not alone, but together. In the standards and in the technical literature there is no data, which expresses the combined effect of warm and cool surfaces. The combined effect of warm ceiling and cool wall (it can be full window surface) can occur for example in an office building with large window surfaces, at the work places next to the window. I examined the combined effect of cool wall and warm ceiling with calculation and measurements.

2.2. Presentation of thermal manikin

A thermal manikin (Figure 2.3.) was used for the measurements. The thermal manikin were made in the 1980's, in Hungarian Institute for Building Science, and it made by Swedish experts. Later, this thermal manikin were in the Technical University of Budapest, Department of Building Service Engineering, then from 2010 for research purposes it has been in University of Pécs, Pollack Mihály Technical Faculty, Department of Building Service Engineering, where the manikin got new, advanced datalogger and processing software. The thermal manikin is a model that is built from thermal measuring body, control unit, datalogger and computer that make data processing and visualization. The measuring body was made from a plastic puppet with a size of an average adult human body. The body is a polyester shell construction fixed with fiberglass. In the caverns of the manikin there are the elements which give the mechanical keeping, and tubes that contain the hidden electrical cables which go to the body parts. The body surface of the thermal manikin was split up into 16 parts in standing position and 18 parts in sitting position (Figure 2.4.). There are heating wires in each part of the body surfaces. The plastic layer gives the electrical insulation, on this there is an average of 0,4 mm thick aluminium layer to achieve the uniform temperature distribution on the whole body surface. The principle of measurement is that accurately measure the electrical power of the heated body part, which ensure the required surface temperature of it. The required surface temperature of body parts was determined at 0 PMV value.

Figure 2.3.
Thermal manikin

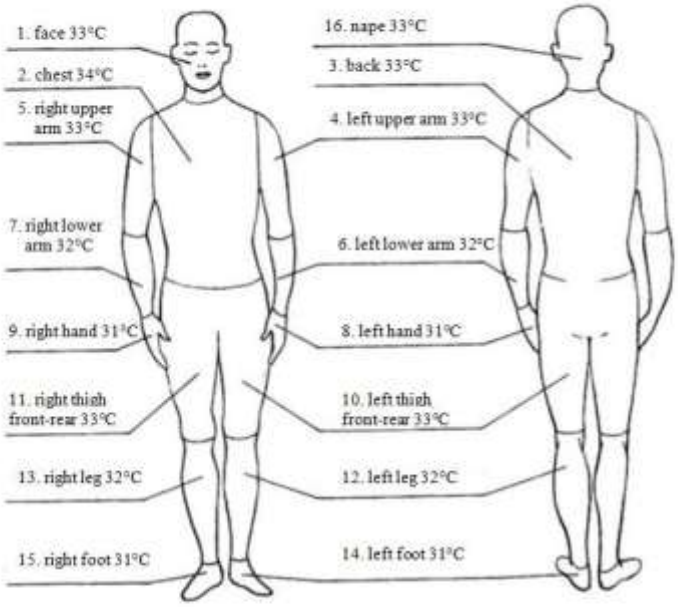

Figure 2.4.
Surface temperature of thermal manikin

2.3. Applicability of thermovision investigations

During the measuring of the temperature the image is made in that way: from an optional range of colors we add colors for the intensity of the infrared radiation, then the colors will shown in the correct position. In the measurement it is very important to know the ambient temperature and the emissivity of the body. The measuring device can only determine the temperature of an object, if in the measuring device (or in the analysis software) the set value of the emissivity correspond the real data. If the object being measured is not an ideal radiant (absolute black) body with $\varepsilon = 1$ emissivity, then ambient temperature must be considered when determining the temperature of the object. By right of calculations and measurements the human skin has a special quality, because the emissivity of it is $\varepsilon = 0{,}95$ (Ashrae, 2009).

Today, the medical science uses the human infrared vision to show structurally the abnormailities in the body, and to determine the type, the location and the extent of these abnormalities. The thermovison measurement can separate the lesions and the different tissues from each other, and can show the physiological and pathological processes. In normal processing the heat of the body is balanced, and it is distributed according to the body parts. The deviation from normal temperature as well as the abnormal regulation of temperature, can show initial or ongoing disease process. The heat producing of a painful, inflamed tumor or poorly functioning, worn parts of the body is differ from normal functioning tissues. The thermovison examination, with the thermal map of human body, is capable to show accuratly the physiological process and the regulation of the body, and thereby it can facilitate the early detection of deseases and more precise clarification of the background of deseases (Figure 2.5.).

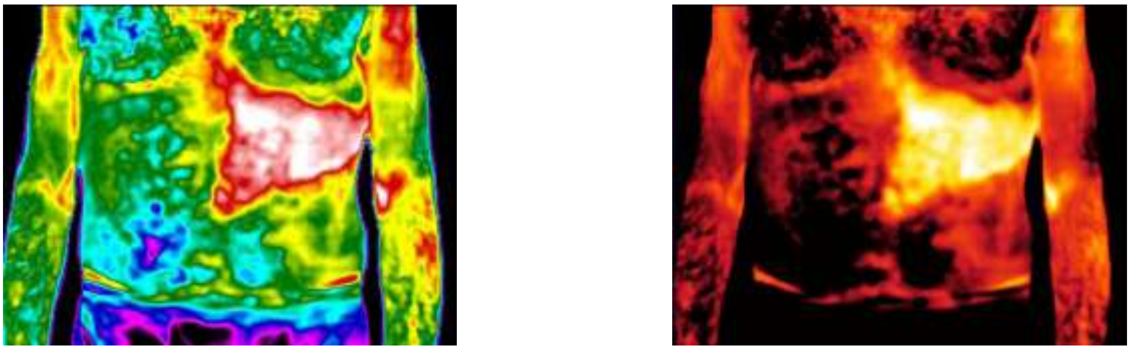

Figure 2.5.
Thermovision examination of different deseases

Application examples:

- Inflammatory musculoskeletal diseases
- Degenerative arthritis-, and spine lesion
- Static problems
- Musculoskeletal disorders due to nervous harm
- Peripheral vascular disorders
- Soft tissue rheumatism (golf, tennis elbow, fibromyalgia, etc.).
- Visual support for some diseases (pain syndrome)
- To set up healing and recovery programs
- Follow-up studies: analysis the efficiency of different treatments
- Compilation of sports programs
- Ergonomics research and work eligibility consultancy
- Assessment of tumor, determine the effectiveness of treatments

2.4. Thermal insulation of clothing

The heat loss and the heat sense of the people are greatly influenced by the thermal insulation of clothing. The convective and radiative heat transfer can be measured on the whole body surface with the thermal manikin. From the surface temperature and heating power datas that measured at the body parts of the thermal manikin, by summation of body part area wighted datas can calculate the heat loss of the whole body and the thermal insulation of the clothing. The total insulation, that is thermal insulation (thermal resistance) of clothing and boundary air layer around clothing, can be calculated as follows:

$$— \qquad (2.2.)$$

where:

I_T – total thermal insulation of clothing and boundary air layer, m^2K/W
I_{cl} – thermal insulation of clothing, m^2K/W
I_a – thermal insulation of boundary air layer, m^2K/W
f_{cl} – clothing area factor, that is the ratio of the outer surface area of the clothed body to the surface area of the nude body, -

To calculate the total thermal insulation we have to measure the heat loss of the thermal manikin dressed in the examined clothing. To calculate the boundary air layer around the body we have to measure the heat loss of the nude thermal manikin. According to the technical literature the parallel and serial calculation method can be used.

The parallel summation calculation method:

The parallel summation calculation method determines the total thermal insulation as an area-weighted average of the local insulations.

(2.3.)

The serial summation calculation method:

The serial summation calculation method is based on the measurement of total thermal insulation by summation of the local area-weighted thermal insulations:

(2.4.)

where (2.3. and 2.4.):

f_i – area factor of section i. of the thermal manikin, f_i = ai/A, -
a_i – surface area of section i. of the manikin, m^2
A – total body surface area of the manikin, m^2
T_i – surface temperature of section i. of the manikin, K
T_a – air temperature in the climate chamber, K
H_i – local heating power fed to section i. of the manikin, W

Calculate by the parallel summation calculation method it results that the total thermal insulation is usually 20 % smaller than the values calculated by the serial method.

We have to calculate the thermal insulation of boundary air layer around the nude body (I_a) similarly to the method of calculation of total thermal insulation.

The clothing area factor – the value of f_{cl} – can be determined by measurement, but approximate, indirect calculation is also possible, which McCullogh and Jones (1985) correlation can be used:

$$f_{cl} = 1 + 0{,}28\ I_{cl} \qquad (2.5.)$$

Thermal insulation of clothing in unit clo:

$$I_{cl} = I_{cl}\,[m^2K/W] / 0{,}155 \qquad [clo] \qquad (2.6.)$$

3. RESULTS

3.1. Comparison of surface temperature of human subjects and thermal manikin

I examined with thermovision measurements, that thermal manikin can be used instead of panel in thermal comfort measurements. The examination contained the measurement of the whole body and the body parts too.

I took thermovision pictures from the thermal manikin and the subjects. I did not measure the absolute value of the temperature, but I compared the surface temperature of the body of the themal manikin and the panel. The surface of the body of the selected subjects were approximately equal to the surface of the body of the thermal manikin (A = 1,9 $m^2 \pm 5$ %), clothing was the same.

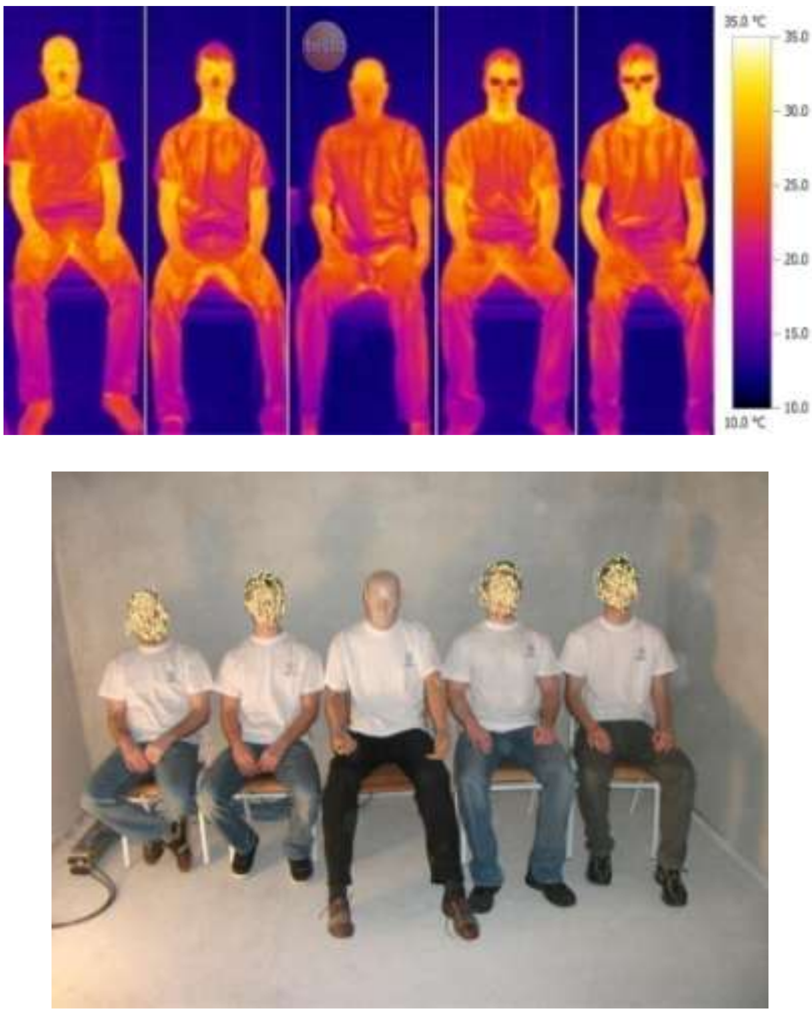

Figure 3.1.
The photo and the thermovision picture of the thermal manikin
and the subjects

I made the thermovision measurements at 15°C, 20°C and 25°C ambient temperatures. The Figure 3.1. shows the surface temperature of the body of the thermal manikin (center) and the subjects at 15°C ambient temperature.

With thermovision measurements, I examined in detail the changes of the body surface temperature along a line at different bodyparts of the thermal manikin and subjects. For example, Figure 3.2. shows, along a line at the height of the chest, the changes of the surface temperature of the body of the thermal manikin and next to it the subject. Along the line the surface temperature is between 24,7°C and 27,2°C for the examined subject, and between 23,6°C and 27,8°C for the thermal manikin.The mean value of the surface temperature of the thermal manikin and the subject was similar (25,9°C).

The comparison was done in different parts of the body (chest, leg, hand). The thermovision pictures at 15°C ambient temperature are in the Annex 3 (M3). Pictures at 20°C ambient temperature are in Annex 4 (M4). And the thermovision pictures at 25°C ambient temperature are in Annex 5 (M5).

Based on my investigations I concluded, that the surface temperature of the subjects and thermal manikin are close to each other, and their average surface temperatures are always within ± 0,5 °C. For further works I determined conclusions for subjects based on the measurements of thermal manikin.

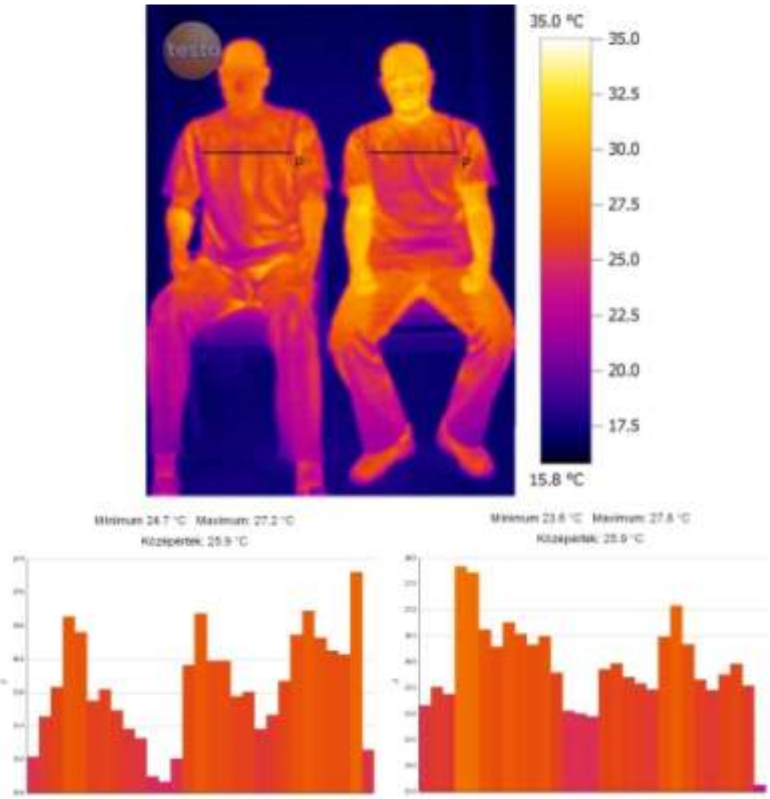

Figure 3.2.

The comparision of the surface temperature of the thermal manikin and the subject, along a line at the height of the chest, at 20 °C ambient temperature.

3.2. Thermal insulation of the clothing in function of air temperature

When I studied the technical literature I did not find any information that expresses how the total thermal insulation depends on the ambient temperature, therefore I examined with thermal manikin measurements, how the total thermal insulation, ie. insulation of clothing and boundary air layer, depends on the ambient temperature. For the calculations I used the relationships described in 2.4. section. The ambient air temperatures were set between 13°C and 20°C in the thermal comfort laboratory, and in the outdoors I measured when the ambient air temperatures were between -3°C and +1°C.

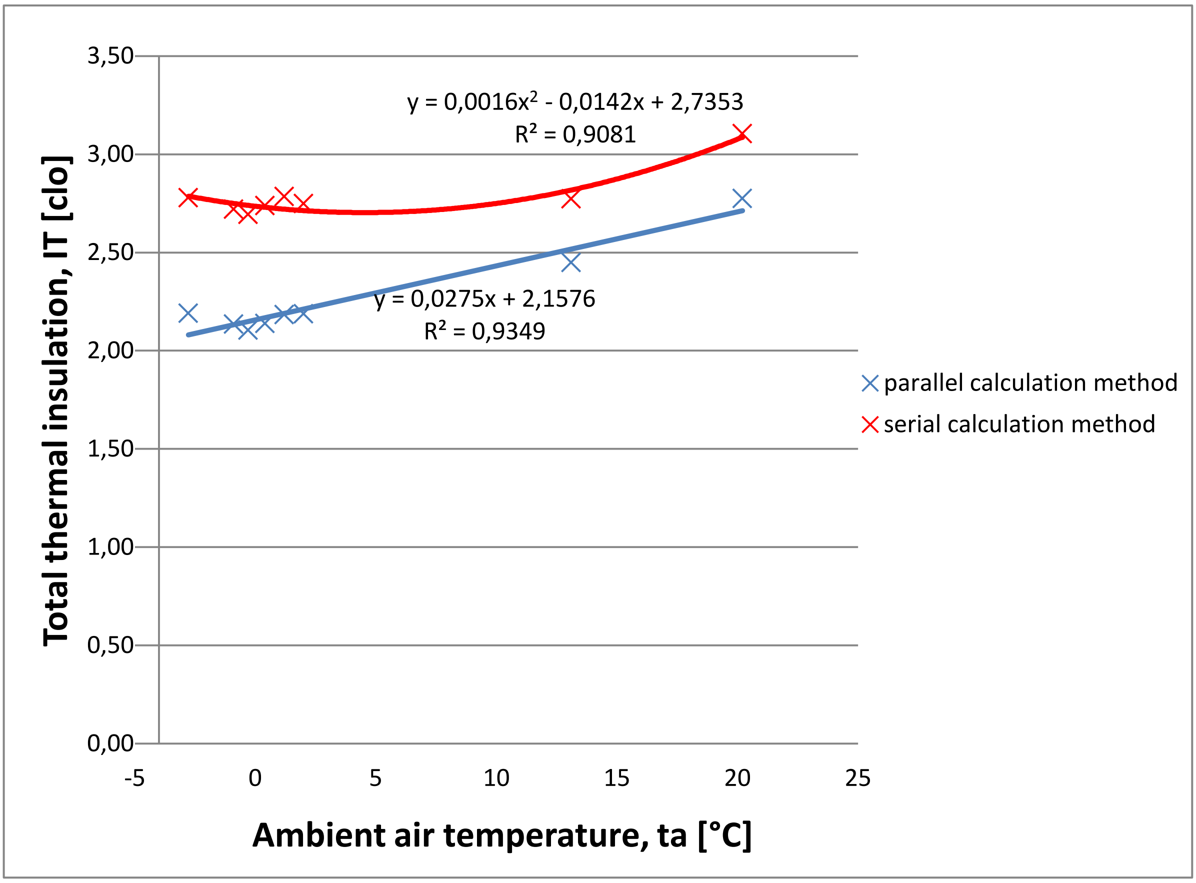

Figure 3.3.

The total thermal insulation as a function of the ambient air temperature

Based on the measured values I concluded, that the thermal insulation of clothing depends on the ambient temperature, it is not reasonable to neglect it. The Figure 3.3 shows the total thermal insulation as a function of the ambient air temperature. Using the serial calculation method the total thermal insulation of clothing increased 11,5%, and using the parallel calculation method it increased 26,7%, between –2,78 °C and +20,2 °C ambient temperature.

Using thermal manikin for the measurement of thermal insulation of clothing, that ambient temperature should be set up, in which the examined clothing is used.

3.3. Heat load of the human body in different equvivalent temperature

The heat loss of the people depends on the air temperature, the radiant temperature of the surrounding surfaces, the air velocity and the relative humidity, the activity and the clothing. In the comfort indoor spaces the heat loss of the people less dependent on the air velocity and humidity, therefore during the investigations I assumed these values are constant. During the investigations the air velocity was v = 0 m/s, and relative humidity was approximately φ = 50 %. With these parameters I measured the heat loss of the thermal manikin in different clothing. During the measurements, the air temperature were equal to the mean radiant temperature of the surrounding surfaces, therefore I determined the heat loss of the people as a function of the equivalent temperature, in different clothes.

The technical literature gives the heat loss of the people as the function of the activity, the value of the heat loss in wide range of temperature has not been known, the determined relationships provide useful information for further research. I determined the heat loss of the people in different clothes as a function of the equivalent temperature. The measurements were carried out between -3 °C and +26 °C ambient temperature, with 1,0 clo normal business man clothing, 1,3 clo business man clothing with raincoat, and 1,5 clo business man clothing supplemented with fabric jacket. The examined range was wider than the comfort indoor space, but the air velocity and relative humidity changes were not examined. The weather conditions have a significal effect for the people who work in outdoor cold spaces, their effects only the clothing can change. The measurement results provide useful relationships for medical science that has not been known.

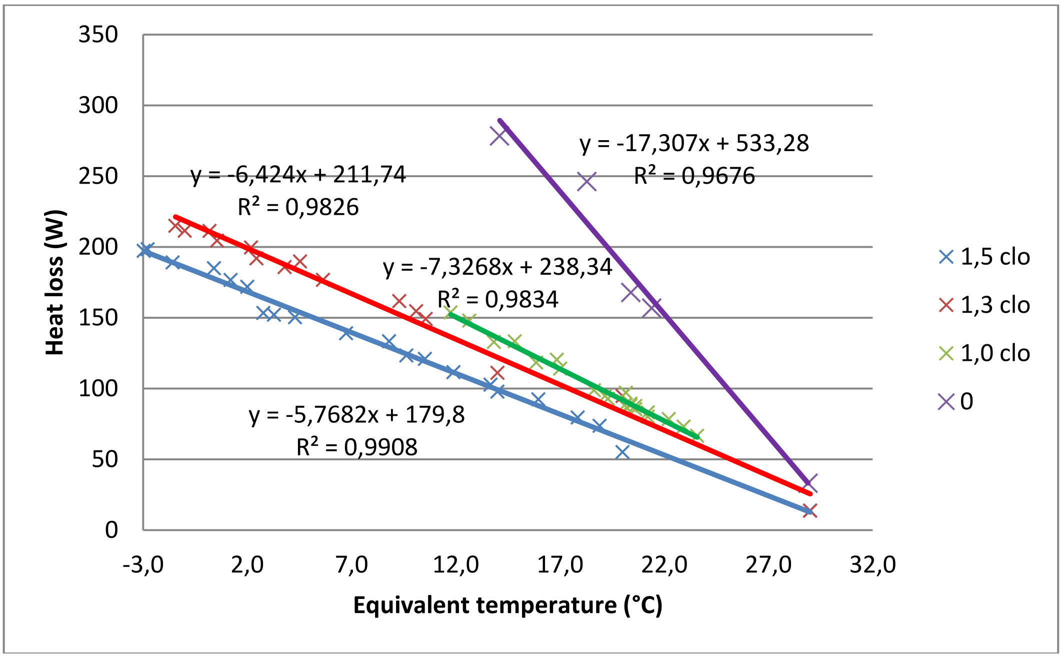

Figure 3.4.
The heat loss of the people as a function of the equivalent temperature, in different clothes

3.4. Heat load of the part of human body in different equvivalent temperature

The medical science and the comfort theory are not only interested in the heat loss of the whole human body, but the heat loss of the bodyparts too. I determined the specific heat loss for the body surface area unit and the heat loss of the whole human body as a function of the equivalent temperature. The measurements were carried out when the thermal manikin was nude, then for different clothing. I concluded that the heat loss of the body parts changes linearly as a function of the equivalent temperature. Without clothing the variance was between 0,8769 and 0,9959 (except the back, which was 0,759), in 1,0 clo clothing it was between 0,8356 and 0,9617, in 1,3 clo clothing it was between 0,9655 and 0,9936, and in 1,5 clo clothing the variance was between 0,7759 and 0,9961. For example on the Figure 3.5. we can see the specific heat loss of the face, the chest and the head as a function of the equivalent temperature, when 1,3 clo clothing covers the body. Annexes 6 - 9 (M6 – M9) of the dissertation contains the heat loss and the specific heat loss of the human bodyparts (18 pieces) as a function of the equivalent temperature, when 0 clo, 1,0 clo, 1,3 clo and 1,5 clo clothing cover the body.

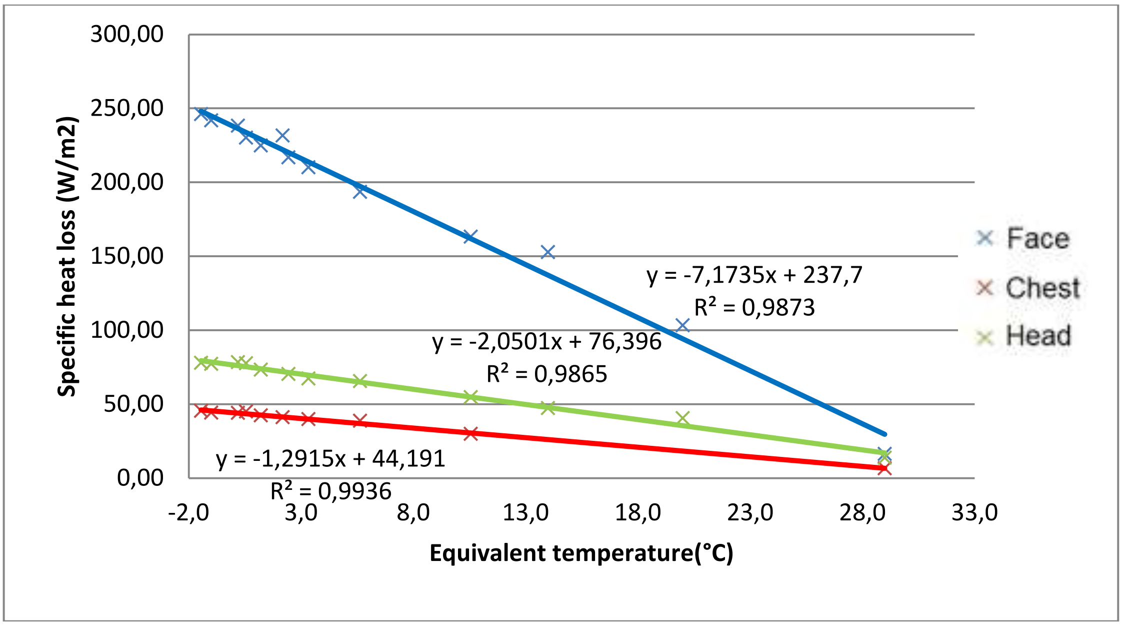

Figure 3.5.
The specific heat loss of the face, chest and the head when 1,3 clo clothing covers the body

The identified relationships show the different heat loss of the body parts, which provide important information for thermal discomfort investigations in the comfort theory and in the medical science for research of different deseases, eg. kidney deseases.

3.5. Radiant temperature asymmetry – theoretical investigaton of common effect of warm ceiling and cool wall

The thermal sense of the people is influenced by the local physical characteristics of the occupied zone. Among of local discomfort factors the investigation of radiant temperature asymmetry is one of the most important, that is when one's mental or physical activity is done in an environment, where, for example cool glass surface, wall heating/cooling or ceiling heating and/or cooling structure is built in the building.

The local thermal comfort is significantly affected by the radiant asymmetry, due to the different temperature of the surrounding surfaces. In the technical literature and in the standards (Figure 2.2.) the percentage of dissatisfied is shown as a function of the radiant temperature asymmetry caused by a warm ceiling, a cool wall, a cool ceiling or by a warm wall. But in practice we can see cases, when the factors causes the radiant temperature asymmetry occur not alone, but together. In the standards and in the literature there is no data, which expresses the combined effect of warm and cool surfaces. The combined effect of warm ceiling and cool wall (it can be full window surface) can occur for example in an office building with large window surfaces, at the work places next to the window.

I examined the combined effect of heated, warm ceiling and cool glass surface in an open-plan office with 21x7 meter area, next to the window edge zone (21 m side, middle), for a work place 1,1 m away from the window. I took into account 1,0 clo clothing (normal businessman clothing), activity 1,2 met (69,6 W/m^2, sedentary office work), average air velocity < 0,1 m/s. I examined two cases for the calculation:

<u>Case 1.</u>

Basic data:

Surface temperature of the inside of the window:	15,5°C
Surface temperature of ceiling:	33°C
Surface temperature of floor and inside walls:	22°C
Air temperature:	22°C

Calculated values:

Operative temperature:	23,70°C
PMV	0,51
PPD	10,4%

<u>Case 2.</u>

Basic data:

Surface temperature of the inside of the window:	16°C
Surface temperature of ceiling:	35°C
Surface temperature of floor and inside walls:	22°C
Air temperature:	22°C

Calculated values:

Operative temperature:	24,66°C
PMV	0,65
PPD	13,8%.

During the investigation, in the first step I determined the operative temperature at the given workplace with the calculation method developed by Fanger (1970), and based on MSZ EN ISO 7730 (2006) standard, I determined the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) as a function of the average air velocity, the thermal insulation of clothing and the activity level. The calculated value of predicted percentage of dissatisfied (PPD) is differed from the value which determined based on the diagram of the standard (Figure 3.6.). If we consider only the cool wall for the radiant temperature asymmetry, in this case the predicted percentage of dissatisfied which determined based on the diagram of the standard (1%) is substantially lower than the calculated value (10,4% and 13,8%). If we consider only the warm ceiling for the radiant temperature asymmetry, however in this case the predicted percentage of dissatisfied which determined based on the diagram of the standard (23% and 30%) is higher than the calculated value (10,4% and 13,8%).

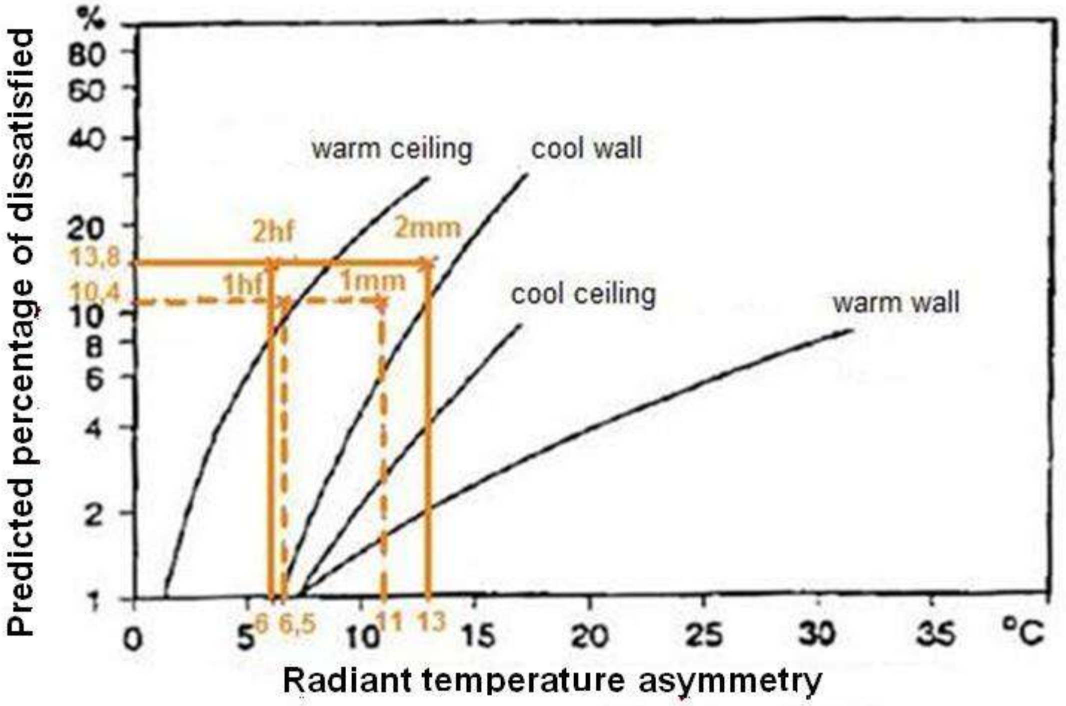

Figure 3.6.
The calculated value of predicted percentage of dissatisfied, taking into account separately the calculated radiant temperature asymmetry of warm ceiling and cool wall

Key for Figure 3.6.:

1hf: In the Case 1. the calculated value of predicted percentage of dissatisfied (10,4%), taking into account the calculated radiant temperature asymmetry of cool wall (6,5°C)

1mm: In the Case 1. the calculated value of predicted percentage of dissatisfied (10,4%), taking into account the calculated radiant temperature asymmetry of warm ceiling (11°C)

2hf: In the Case 2. the calculated value of predicted percentage of dissatisfied (13,8%), taking into account the calculated radiant temperature asymmetry of cool wall (11°C)

2mm: In the Case 2. the calculated value of predicted percentage of dissatisfied (13,8%), taking into account the calculated radiant temperature asymmetry of warm ceiling (13°C)

It can be concluded, that the combined effect of warm ceiling and cool glass surface can not be examined with the known method, ie. with the curve for the warm ceiling or for the cool wall.

3.6. Radiant temperature asymmetry – investigaton with thermal manikin of the common effect of warm ceiling and cold wall

I modeled the internal heat production of human body with thermal manikin. The heat production is changing according to the different external conditions (for example cool wall/window and warm ceiling). The measurings were carried out in the thermal comfort laboratory of University of Pécs, Pollack Mihály Technical Faculty, Department of Building Service Engineering. The measuring laboratory is 3 x 4 meters and its height is 3 meters. The thermal manikin was located 1,1 m apart from the cool wall (Figure 3.7.). The temperature of the floor, the ceiling and every wall of the laboratory can be measured and can be set. The time of one measuring was about 4 hours, of which the temperature settings of the walls were 3 hours, and the measuring with the thermal manikin were about 1 hour. From the datas of the 1 hour-measurements I made an average, and that was I used to evaluate the measurements.

I measured the heat loss of the body parts, and in addition I measured the black globe temperature near the thermal manikin, and the air temperature at height of 0,1 meter and 1,1 meter (the height of ankle and neck when somebody works in sitting postion) for the examination of local thermal comfort.

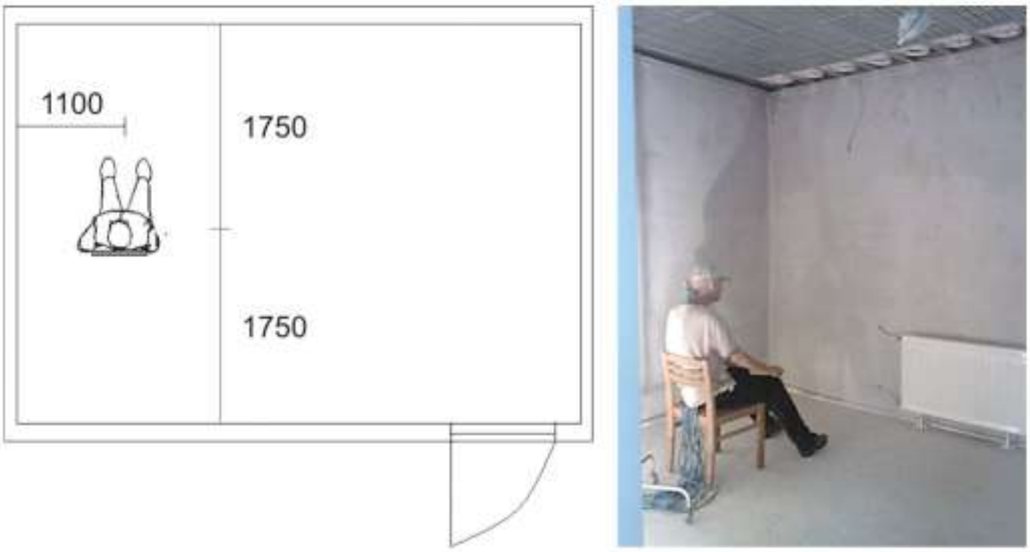

Figure 3.7.

The thermal manikin in the laboratory

First, the aim of the measurements was to determine the heat loss of the thermal manikin, when there were cool wall/windows, warm ceiling and combination of cool wall/windows and warm ceiling. Second, in the next part of the measurement I modeled a given workplace of an office, and I examined the effect of the radiant temperature asymmetry with thermal manikin.

In the course of the measurements I examined the heat loss of the thermal manikin in three different situations. In the first measurement series, I set the cooled wall temperature to the usual value, between 17 and 22 °C. In the laboratory, the temperatures of all other surfaces were 22°C. I also measured the supply and the return temperature of the chilled water which cooled the wall, and I measured the operative temperature and the air temperature at height of 0,1 meter and 1,1 meter (the height of ankle and neck when somebody works in sitting postion).

In the second measurement series, the position of thermal manikin was not changed, but I heated the ceiling and I made the measurements at the usual values, between 27 and 30°C of ceiling temperature. I set the temperatures of all other surfaces to 22°C.

In the third measurement series, the cooling of the wall and the heating of the ceiling was operated according to the previously set values.

I made measurements when the thermal manikin wore typical business clothes (1 clo), summer clothes (0,75 clo) and when it was nude (0 clo).

The results of the measurements in 1 clo clothing

The Figure 3.8. shows the results of the three different measurements when thermal manikin wore 1,0 clo clothing. The largest heat loss was measured at cool wall and least heat loss was measured at heated ceiling. The heat loss of the thermal manikin was 82,5 W at cooled wall, and 51,8 W at heated ceiling, that is 30,7 W difference. When both systems were operated simultaneously, the heat loss was between the results of previous two measurements. In all three situations increasing the temperature caused decreasing the heat loss.

I determined the heat loss of the different parts of the body. On the Figure 3.9. we can see, that in all three situations, the back, the legs and the face have the maximum heat loss of the bodyparts.

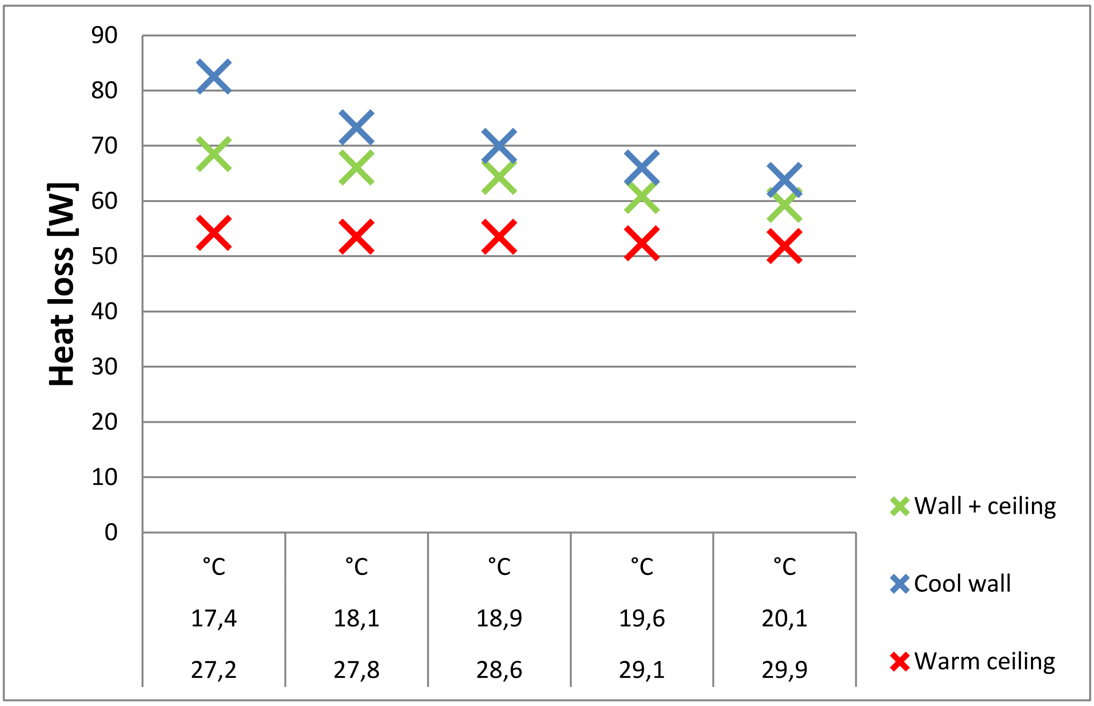

Figure 3.8.
The heat loss [W] of thermal manikin in 1,0 clo clothing

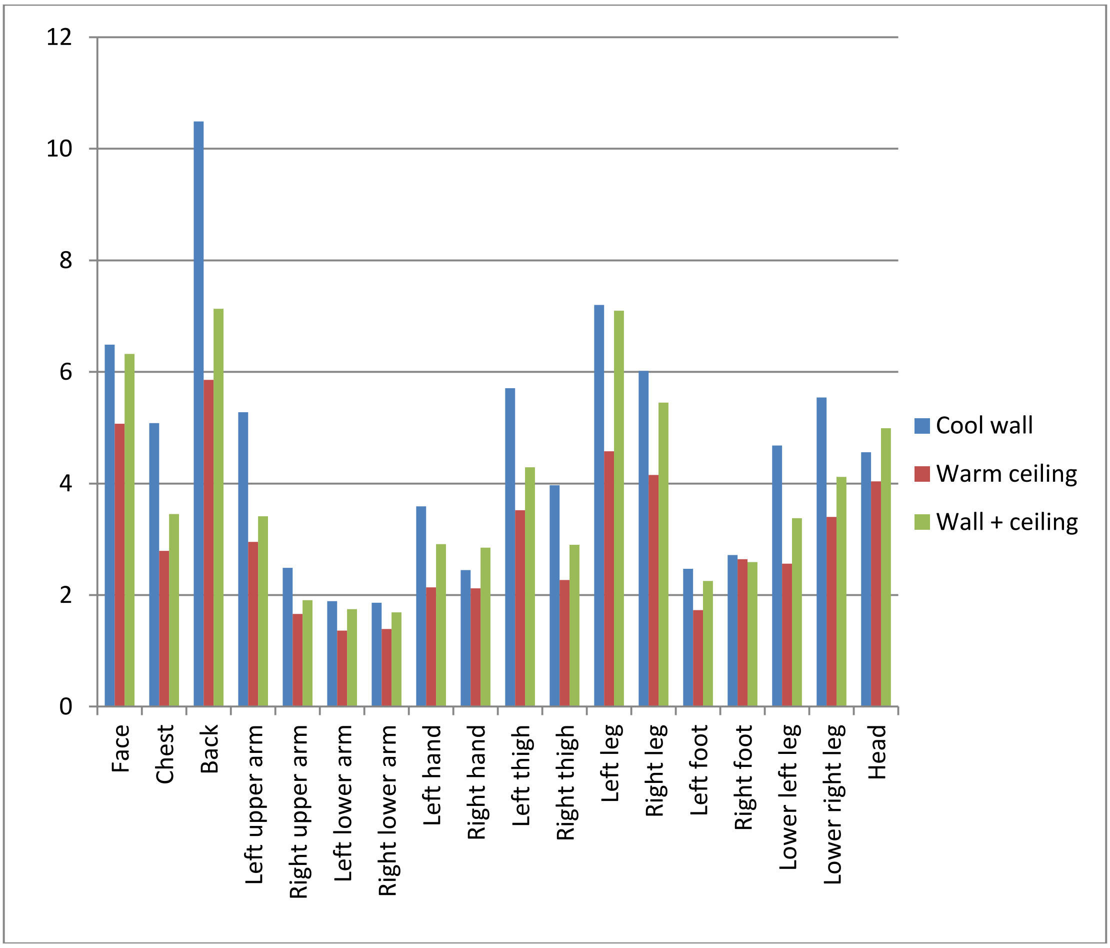

Figure 3.9.
The heat loss [W] of the bodyparts in 1,0 clo clothing at different heating-cooling

The results of the measurements in 0,75 clo clothing

On the Figure 3.10. we can see the heat loss of the thermal manikin when the manikin wore 0,75 clo clothing. In this situation we can see that the effect of the cooled wall and the combined effect of cooled wall and heated ceiling are similar, the value of the heat loss of the thermal manikin is close to each other. There is a similar trend at the heat loss of the bodyparts too (Figure 3.11.).

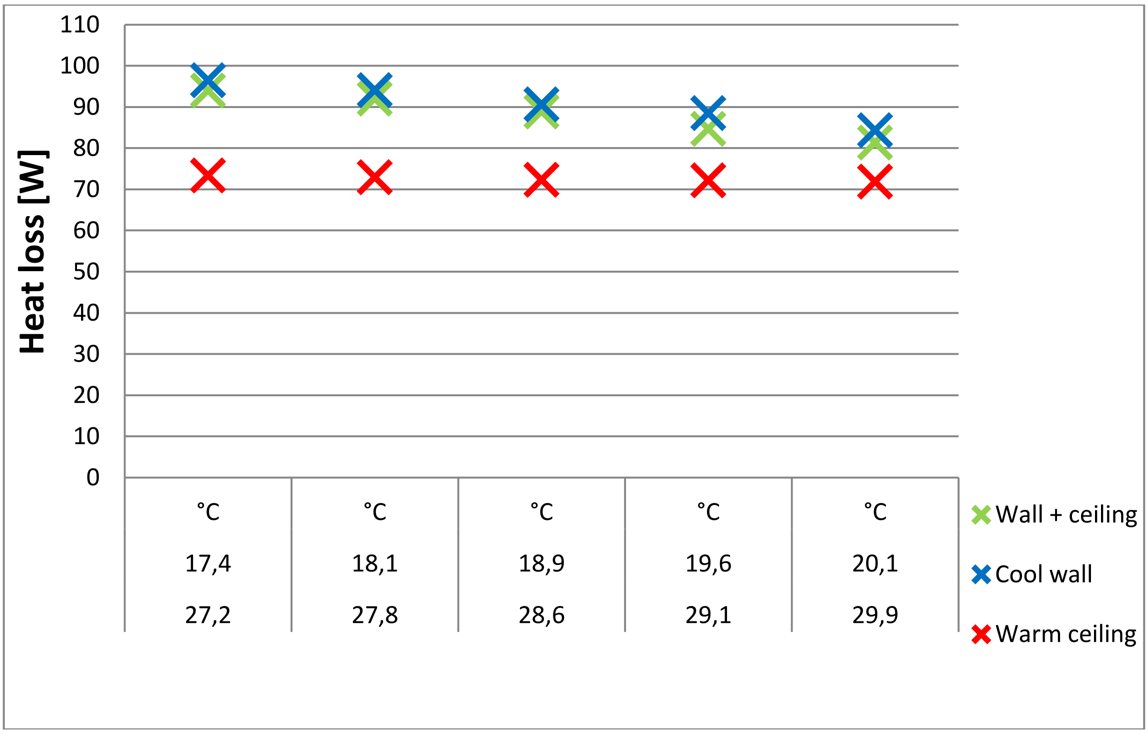

Figure 3.10.
The heat loss [W] of thermal manikin in 0,75 clo clothing

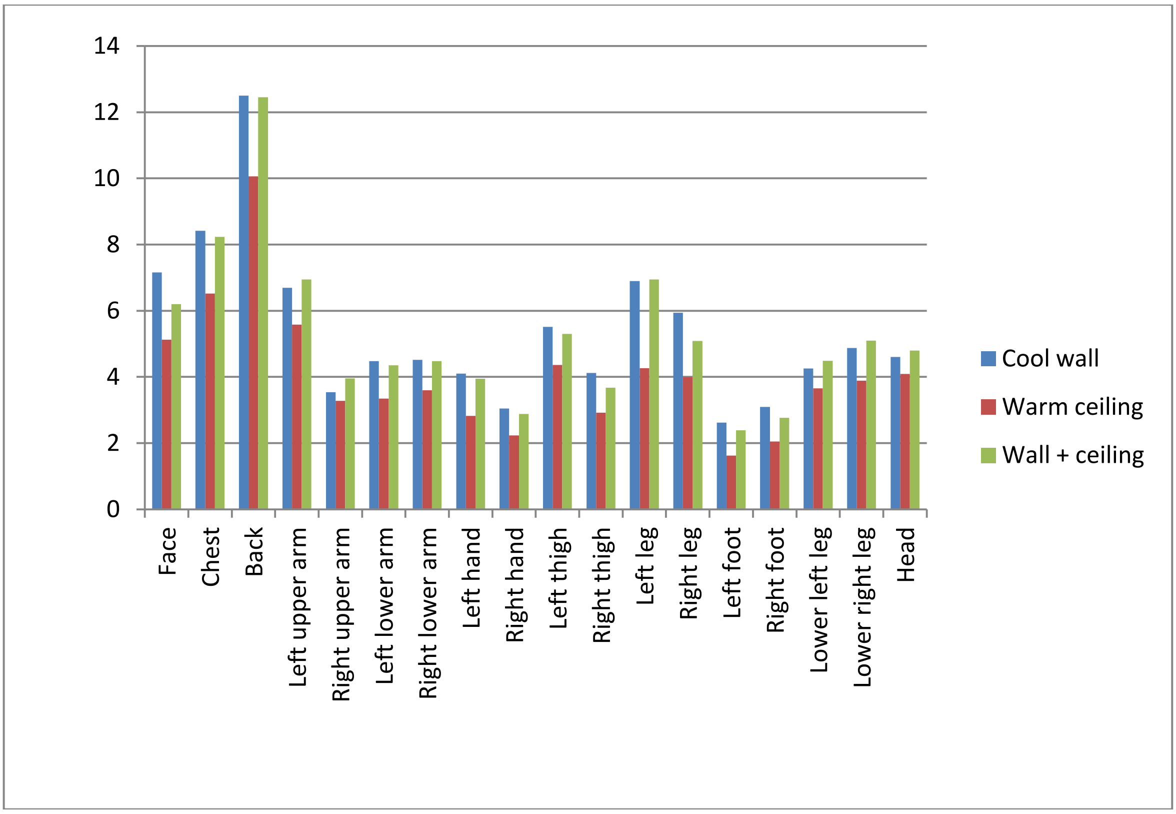

Figure 3.11.
The heat loss [W] of the bodyparts in 0,75 clo clothing at different heating-cooling

The results of the measurements when thermal manikin is nude (0 clo)

On the Figure 3.12. we can see the heat loss of the thermal manikin when the manikin was nude. In this case the changing is smooth. I measured the largest heat loss at cool wall and the least heat loss at heated ceiling. The combined effect of the cooled wall and heated ceiling caused that the heat loss was between the results of previous two measurements. There is a similar trend at the heat loss of the bodyparts too (Figure 3.13.).

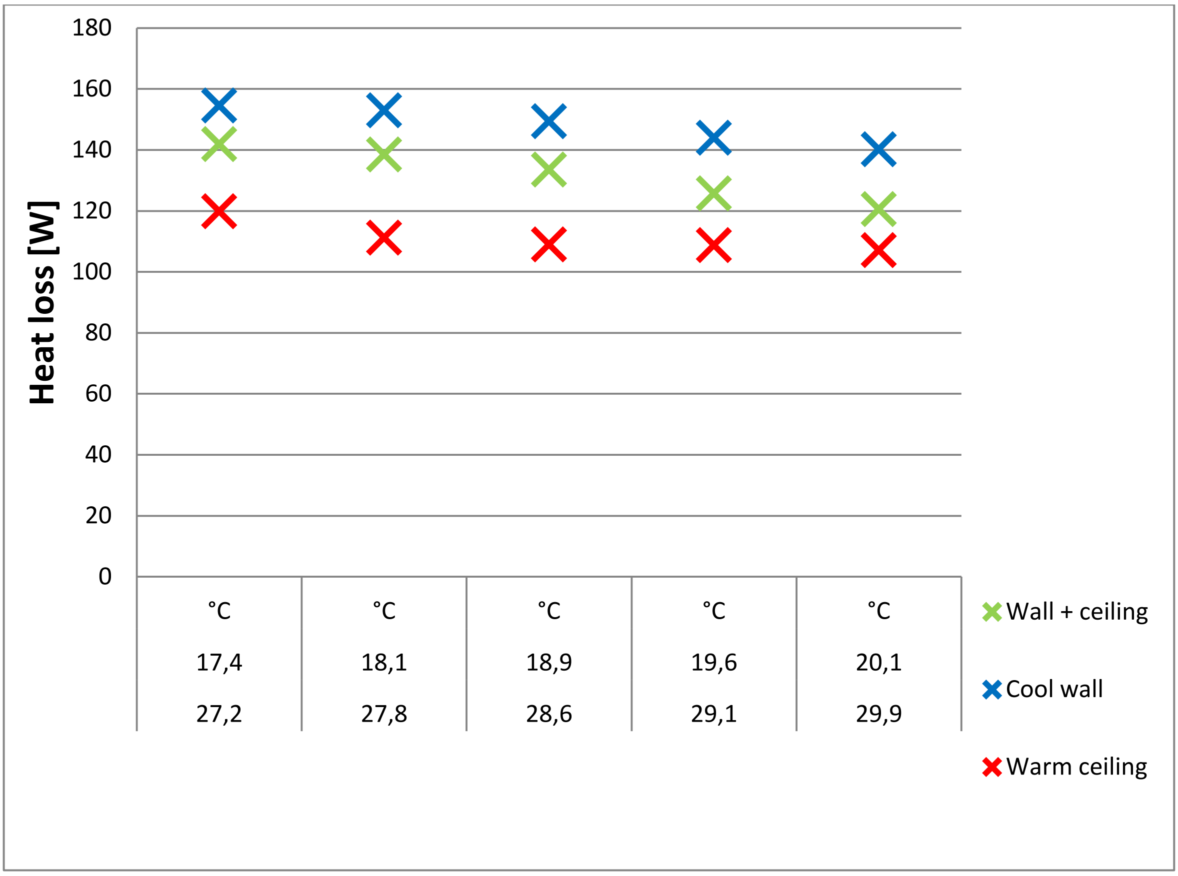

Figure 3.12.
The heat loss [W] of the nude thermal manikin

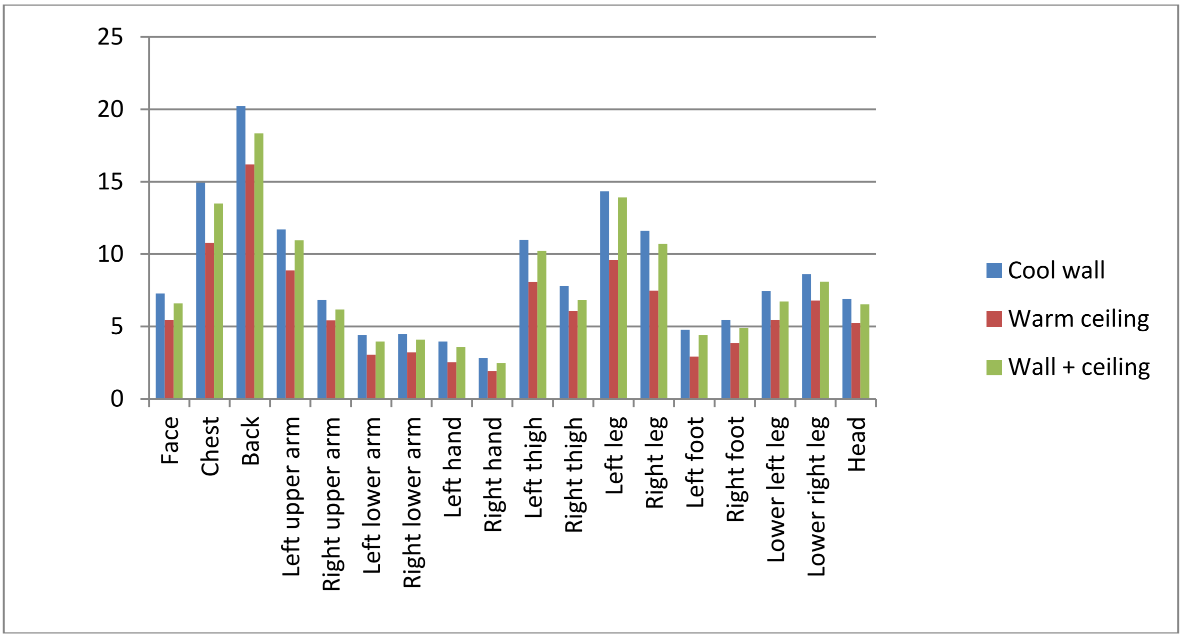

Figure 3.13.
The heat loss [W] of the bodyparts of the nude thermal manikin at different heating-cooling

Conclusions

I set the temperature to 22°C of all surrounding surfaces, except the examined cooled wall/window and/or heated ceiling, which temperature were varied. The obtained results show that I measured the largest heat loss at the cooled wall, the least heat loss at the heated ceiling when the thermal manikin wore 1,0 clo clothing. When the cooled wall and the heated ceiling were operated simultaneously, the values of heat losses were between the results of the two measurements. In every situation and all 3 clothings I determined the heat loss and the specific heat loss of the bodyparts (18 pieces). The specific heat losses of the bodyparts were between 16,1 – 133,3 W/m^2. The result can be starting point for further thermal sensation analysis, and the knowledge of the heat losses of different bodyparts provides useful information for the medical science for research different deseases.

3.7. Modeling of office workplace with thermal manikin

According to the 3.5. chapter, the examination was made in an open-plan office with 21x7 meter area, next to the window edge zone, for a sitting work place 1,1 m away from the window. I made the examination for a workplace located in the corner of the office, where the left side and the back of the employee are 1,1 m apart from the cool window surface, while heated ceiling provides the heat supply of the room. I set the temperature of the ceiling 22°C (the heating system does not operate) and 33°C (the heating system operates). The other parameters were set according to the usual characteristics: 22°C air temperature, 1,0 clo thermal insulation of clothing, 1,2 met activity.

I compared the measurement results with the reference state, where the temperature of every surrounding surface is 22°C, the thermal insulation of the clothing is 1,0 clo and the thermal manikin is in a sitting position in the middle of the laboratory. In the reference state I measured the heat production of the bodyparts, the air temperature at height of the neck and the ankle, the black globe temperature. The measured values were compared with the values in the reference state.

When I modelled the work place, in the measurement series 1. and 2. I set the temperature of the surface left to the thermal manikin according to the temperature of the inside of the window. In the measurement series 3. and 4. I also set the temperature of the surface behind the thermal manikin according to the temperature of the inside of the window, therefore the thermal sensation of the employee which works in the corner can be examined (first number of the measurement series).

In the measurement series 1. and 3. I examined the typical operating conditions during daytime, when the ceiling heating does not operate (22°C) due to the internal heat load, and the temperatures of the windows are 19,8°C. In the measurement series 2. and 4. I examined the typical operating conditions during weekends and nights, when there is not heat load, the temperature of the heated ceiling is 33°C, and the temperatures of the windows are 16,7°C.

During the measurements I examined the followings:

- the effect of thermal insulation of clothing to the heat production of human body (the second number of the measurement identification, 1 clo and 0,75 clo);
- the effect of the distance from the cool surface left to the thermal manikin to the heat production of human body (0,6; 1,1 and 1,3 meter – the third number of the measurement identification).

On the Figure 3.15. we can see the increasing of the heat production of the human body compare to the reference state, increasing was between 4 % and 30,6 %. I concluded, that if we reduce the thermal insulation of clothing from 1,0 clo to 0,75 clo, the heat production of the human body 0,6 m away from the window will increase 9,8-16,3%. With one cool surface the increasing was 9,8% when the heated ceiling was operated, and 10,8% when it was not operated. The increasing was 16,3% and 11,9% at the workplace in the corner of te office.

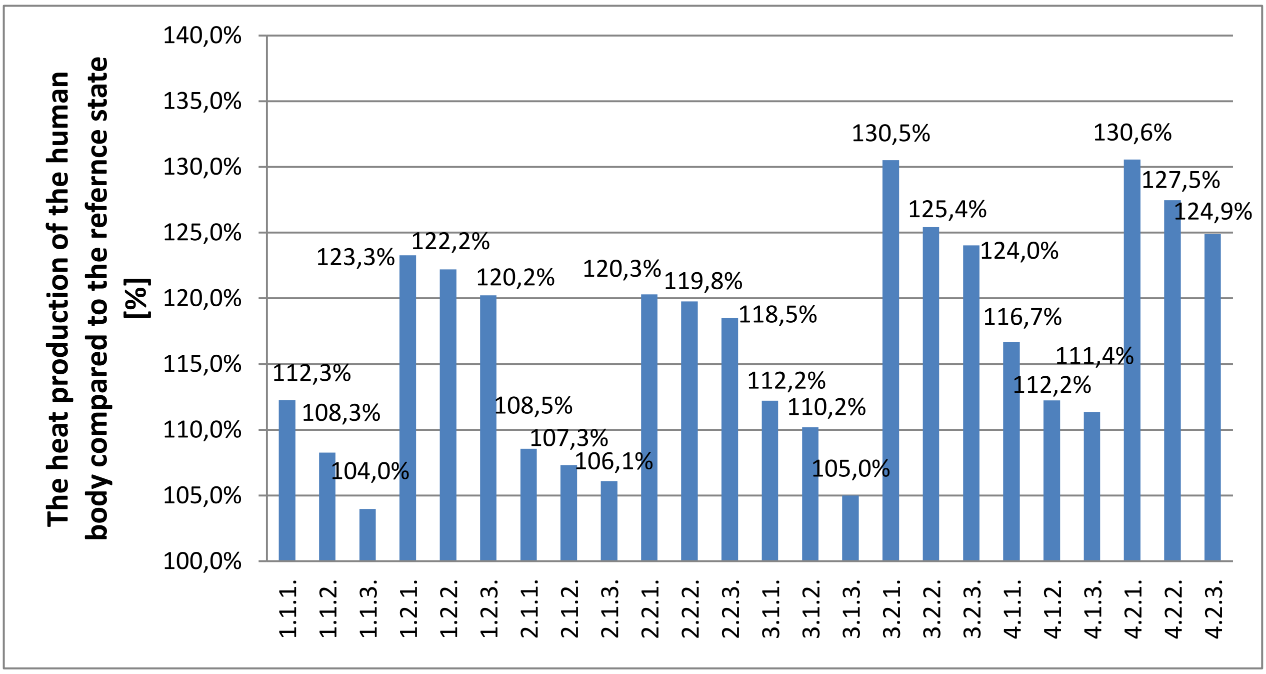

Figure 3.15.
The changing of the heat production of the human body in the different examined situations compared to the reference state

The Figure 3.16. shows the heat loss of the human body as the function of the distance from the cool wall, when the thermal manikin wore 1,0 clo clothing. I concluded, that at the workplace near the window, when the people wear 1,0 clo clothing, the heat loss of the human body decrease linearly when the distance from the window increase. In the examined situations the variances were between 0,9658 and 0,9997. When the heated ceiling did not operate, increasing the distance from the window from 0,6 m to 1,3 m resulted that the heat loss of the human body decreased 6,5% (also in one and two cool surfaces). When the heated ceiling operated, the decreasing of the heat loss was 4%, but in this case at the workplace in the corner of the office (two cool surfaces) the value of the heat loss was 6% higher regardless of the distance.

The concludings apply to office working. In case of other metablic load, the thermal manikin is capable to preliminary research.

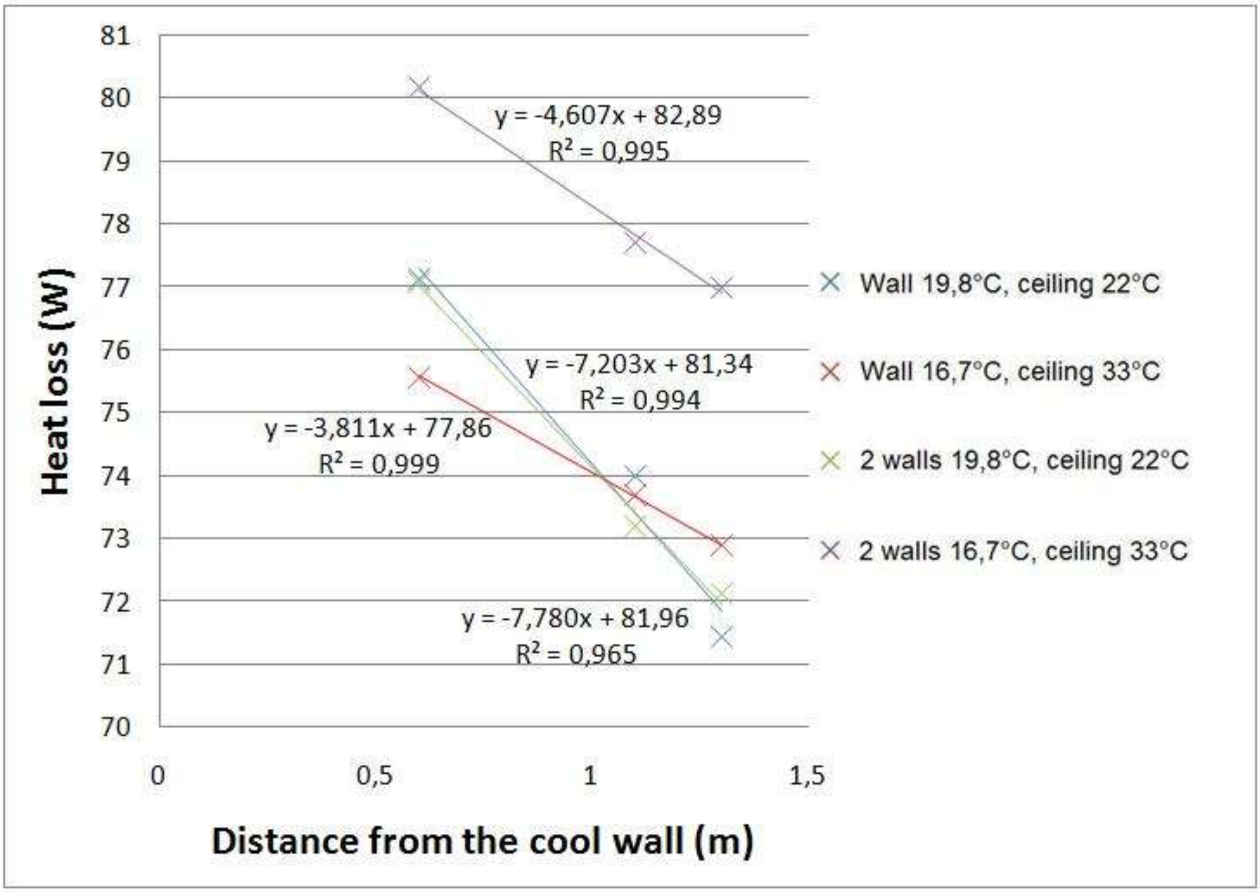

Figure 3.16.
In 1 clo clothing, the heat loss of the people as a function of the distance from the cool wall

4. NEW SCIENTIFIC RESULTS

1. Thesis

Originally the thermal manikins were developed to examine the thermal insulation of clothing of the American military clothing. Later, the thermal manikins have been used for thermal comfort researches. I made my researches with thermal manikin which prepared by the Hungarian Institute for Building Science.

It was proved, that preliminary and in some cases precisely, the thermal manikin is capable to determine the heat loss of the human body rather than using healthy human subjects. This conclusion is valid not only for the whole human body, but it is valid to determine the heat loss of the body parts too. This scientific recognition allows the examination of clothing and thermal comfort and in addition the examination of health parameters with thermal manikin.

The conclusion based on simultaneously made examinations of thermal manikin and human subjects. With thermovision measurements I examined the whole body and in addition I examined in detail the changes of the body surface temperature along a line at different body parts of the thermal manikin and human subjects. I concluded my investigations, that the mean values of the surface temperatures along a line and the values of surface temperatures of panel and thermal manikin are close to each other, it meets the requirements of technical practises, therefore the thermal manikin measurements provides a good estimate regarding healthy humans.

2. Thesis

The literature gives the heat loss of the people only as a function of the activity, the value of the heat loss defining in wide range of temperature has not been known in the comfort theory and in medical research. The equivalent temperature is important at the thermal comfort measurements made with thermal manikin. The equivalent temperature is the temperature of an imaginary enclosure with the mean radiant temperature equal to air temperature, no air movement and the person has the same heat exchange by convection and radiation as in the actual conditions.

I determined the specific heat loss for the body surface area unit and the heat loss of the whole human body as a function of the equivalent temperature. I concluded that the function is linear, and the variance value were between 0,9676 and 0,9908.

The heat loss of the whole human body as a function of the equivalent temperature, at different clothing:

0,0 clo clothing	$Q = -17{,}307\ t_{eq} + 533{,}28$ [W]	$R^2 = 0{,}9676$
1,0 clo clothing	$Q = -\ 7{,}3268\ t_{eq} + 238{,}34$ [W]	$R^2 = 0{,}9834$
1,3 clo clothing	$Q = -\ 6{,}424\ t_{eq} + 211{,}74$ [W]	$R^2 = 0{,}9826$
1,5 clo clothing	$Q = -\ 5{,}7682\ t_{eq} + 179{,}8$ [W]	$R^2 = 0{,}9908$

3. Thesis

The medical science and the comfort theory not only interested in the heat loss of the whole human body, but the heat loss of the body parts too. The measurements were carried out when the thermal manikin was nude, then he wone different clothing. I examined all parts of the body which is covered completely by clothing (eg. back, upper arm) and the body parts without clothing (eg.face).

With thermal manikin I determined the heat loss of the body parts and the specific heat loss of the body parts as a function of the equivalent temperature, in different clothes (0,0; 1,0; 1,3; 1,5 clo). I concluded that the heat loss of the body parts (18 pieces) changes linearly as a function of the equivalent temperature. Without clothing the variance value was between 0,8769 and 0,9959 (except the back, which was 0,759), in 1,0 clo clothing it was between 0,8356 and 0,9617, in 1,3 clo clothing it was between 0,9655 and 0,9936, and in 1,5 clo clothing the variance value was between 0,7759 and 0,9961.

The identified relationships show the different heat loss of the body parts, which provide important information for the comfort theory for thermal discomfort investigations and for the medical science for research different deseases, for example kidney deseases.

4. Thesis

The clothing of the people, the thermal insulation of the clothing (clo) is one of the input parameter of the thermal comfort examinations. The thermal manikin is capable to determine the thermal insulation of different garments and clothing. I determined the thermal insulation with two known methods, the parallel and the serial method. Using the parallel summation calculation method I determine the total thermal insulation as an area-weighted average of the local insulations, while the serial summation calculation method is based on the measurement of total thermal insulation by summation of the local area-weighted thermal insulations. The different calculation methods in the literature give slightly different results, but none of them take into consideration that the thermal insulation of clothing depends on the ambient temperature.

I dressed the thermal manikin in winter clothing and I determined how the total thermal insulation of clothing depends on the ambient temperature. I proved that during the determination of thermal insulation of clothing we can not ignore the changing of the ambient temperature. Using the serial calculation method the total thermal insulation of clothing increased 11,5%, and using the parallel calculation method it increased 26,7%, between –2,78 °C and +20,2 °C ambient temperature.

During the thermal manikin measurement of thermal insulation of clothing, that ambient temperature should be set up, which the examined clothing is used.

5. Thesis

The local thermal comfort is significantly affected by radiant asymmetry, due to the different temperature of the surrounding surfaces. The combined effect of warm ceiling and cool wall can occur for example in an office building with large window surfaces, at the work places next to the window. The structure and the heat storage capacity of the window and the wall are not the same, but assuming the same internal surface temperature, the heat exchange between the human and structure will be the same.

I proved with calculations, that the combined effect of warm ceiling and cool glass surface can not be examined with the known method, ie. with the curve for the warm ceiling or for the cool wall.

Currently, there is not a method which available for the examination of the aboved combined effect, and the measurements with human panel would be highly cost- and time-consuming because of the many variable parameters.

6. Thesis

I examined the heat loss of the thermal manikin for cool wall/window (17,4 – 21,2 °C), warm ceiling (27,2 – 29,9 °C), and for the case has not been examined, when the combined effect occurs. I made measurements when the thermal manikin wore typical business clothes (1 clo), summer clothes (0,75 clo) and when it was nude (0 clo).

In the examined temperature range based on the measured values I concluded, that most of the heat loss of the thermal manikin was next to the cool wall/window, and the least heat loss was at the heated ceiling. When the cooled wall and the heated ceiling were operated simultaneously, the values of heat losses were between the results of the separately measured cooled wall and heated ceiling measurements. In every examined surface temperature and all 3 clothings I determined the heat loss and the specific heat loss of the body parts (18 pieces). The specific heat losses of the bodyparts were between 16,1 – 133,3 W/m^2.

The result can be starting point for further thermal sensation analysis, and the knowledge of the heat losses of different body parts provides useful information for the medical science for research different deseases.

7. Thesis

I make a model of office workplace and I examined with thermal manikin measurements how affect the thermal insulation of clothing and the distance from the window, the heat loss of the human body. I compared the measurement results with a reference state, where the temperature of every surrounding surface was 22°C, the thermal insulation was 1,0 clo and the thermal manikin is in a sitting position in the middle of the measuring laboratory. The increasing of the heat production of the human body comparing to the reference state, increasing was between 4 % and 30,6 %.

I concluded, that if we reduce the thermal insulation of clothing from 1,0 clo to 0,75 clo, the heat production of the human body 0,6 m distance from the window will increase 9,8-16,3%. With one cool surface the increasing was 9,8% when the heated ceiling was operated, and 10,8% when it was not operated. The increasing was 16,3% and 11,9% at the workplace in the corner of te office.

I concluded, that at the workplace near the window, when the people wear 1,0 clo clothing, the heat loss of the human body decrease linearly when the distance from the window increase. In the examined situations the variance values were between 0,9658 and 0,9997. When the heated ceiling did not operate, increasing the distance from the window from 0,6 m to 1,3 m resulted that the heat loss of the human body decreased 6,5% (also in one and two cool surfaces). When the heated ceiling operated, the decreasing of the heat loss was 4%, but in this case at the workplace in the corner of the office (two cool surfaces) the value of the heat loss was 6% higher regardless of the distance.

The concludings apply to office working. In case of other metablic load, the thermal manikin is capable to preliminary research.

5. CONCLUSIONS AND SUGGESTIONS

A basic human needs that in the given building there should be such comfort parameters, in which the people feel well. But we should ensure the appropriate comfort with the least energy use.

Usually the thermal comfort examinations are made with living human subjects. The thesis examines another option, the thermal manikin measurements. The thesis shows the applicability of the thermal manikin for thermal comfort measurements, including the comparing of the thermal manikin and human panel. I proved with the measurements, that the thermal manikin can use for thermal comfort examinations instead of human subjects.

I examined the applicability of the thermal manikin in some typical situation, which not yet examined. For example the changes of clothing insulation depending on the ambient air temperature, the heat loss of the whole human body and different body parts depending on different equivalent temperatures, and the research of radiant temperature asymmetry, where have not been examined the combined effect of warm ceiling and cool wall/windows.

The presented examples show the further applicability of the thermal manikin for thermal examinations. The research of the temperature radiant asymmetry with thermal manikin gives new scientific results. The combined effects have not been examined yet. Further complex investigations (eg. warm wall and cool ceiling, or more warm wall,...) gives help for the thermal comfort sizings.

The thermal manikin measurements can be used for those fields, which have not been examined or those that examined, but in another way:

- Modeling the heat exchange of the whole human body or a part of the human body.
- Analysis of the heat losses of body parts, for medical diagnostic.
- The measurement of thermal insulation of old clothing and new clothing, which is in design phase.
- Radiant temperature asymmetry: examination of the combined effects.
- Thermal sensation examination and modeling of workplaces.
- Complex examination of satisfying the comfort requirements and the energy needs.
- Examination of heat loss of the body and the body parts of not healthy people (eg. handicapped)

6. SUMMARY

During my research work I performed the realization of the aims after the review of the technical literature.

I reviewed the technical literature concerning the measurements of the thermal manikins and indoor climate. The thermal environment is depended from the air temperature, relative humidity, velocity, average radiant temperature of surround surfaces, and activity and clothing of the occupant. The heat balance of the human body is the basic of thermal comfort calculation of occupant spaces. It is expressed by the comfort equation. Comfort equation is based on the heat balance of the all human body, which could be inaccurate in the non-uniform thermal conditions (e.g. different temperature of the surround surfaces).

I prepared a hypothesis for my research using the thermal manikin instead of panel for the comfort investigates. I justified with thermo graphic pictures, that the surface temperatures of the thermal manikin and the panel are within ± 0,5 °C. Using thermal manikin we can measure the heat balance of the human body, the convective and radiant heat transfer of the all body. Depend of number of the segment the resolution could be very high. Using thermal manikin we can model the heat condition of the human body and the distribution of the surface temperature of human skin. I justified that the thermal manikin instead of panel is suitable for thermal comfort investigates. The application is valid not only for the all body, the different part of the body, also.

The heat load and production of human being is influenced by the thermal insulation of clothing. Measuring the surface temperatures of the thermal manikin and the heat production we can calculate the thermal insulation of clothing. Using the thermal manikin I justified the correlation between the thermal insulation of clothing and the environmental temperature.

Function of the equivalent temperature I defined the heat production of the whole human body and the different part of the body. I also defined the specific heat production. I made the measurements with thermal manikin naked and dressed in different clothes. I justified linear relationship between the equivalent temperature and the heat production of the human body. It can give important information for the investigation of the radiant asymmetry and for the medical science researching the different illnesses like kidney disease.

The thermal comfort depends from the radiant asymmetry. I justified with calculation that no possible to use the existing method together for warm ceiling and cool wall. I modelled with thermal manikin the heat production of the human body when we use together the warm ceiling and cool wall/window. I investigated the correlation between the heat production of the human body and the distance from the cool wall/window.

The results can be use for further thermal comfort investigations and knowledge of the heat transfer of the part of the human body can use for medical science researching different illnesses.

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