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Influence of Body Moisture on the Thermal Insulation of Sleeping Bags

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Abstract

The influence of body moisture on the insulation properties of 10 different sleeping bags, designed for extreme conditions below –30° C, as well as the capability to be used at such low temperatures was investigated in a shared research project of TNO and EMPA. The sleeping bags were assessed with standardised laboratory tests, human subject tests and a system assessment with specialised apparatus. It turned out that the moisture released at such low temperatures leads to condensation within the sleeping bag and ice between the bag and the underlay which reduces the thermal insulation considerably. Even at –20° C both human subject tests and laboratory measurements demonstrate that the sleeping bags investigated have already reached or even exceeded the limit for which comfortable sleep is possible. Details on the limits of use given by the manufacturers are normally based on computer calculations. With two different computer models the calculated temperature ranges were compared to the measurements. It seems necessary to make further investigations in the field of simulation of heat and moisture transfer through complex compositions of textile layers.

Introduction

Sleeping bags intended for use at very low temperatures have to fulfil certain safety aspects, especially concerning the thermal insulation, in order to allow a safe and comfortable sleep. Even at low ambient temperatures when one tends to feel cold a certain amount of moisture, called perspiratio insensibilis (ca. 22 g/h [1]), is released from the body. This moisture normally released in a gaseous state to the ambient air is transported through the textile layers in which it could condense or even freeze. The evaporation of sweating water extracts a considerable amount of energy from the body. At low temperatures up to 80% (see figure 4) of the released moisture condenses inside the sleeping system which reduces the thermal insulation.

Different methods are used to define the maximum range of use for sleeping bags. As this could lead to uncertainties when comparing different sleeping bags it was decided to learn more about the real limits of use. One of the main aims of this project is to study the influence of moisture on the temperature range within which a sleeping bag can still be used comfortably.

Scope of the project

Both research laboratories have been investigating the optimisation of sleeping bags for manufactures as well as the Dutch (Netherlands) and Swiss army for several years [5]. TNO has specialised knowledge and many years of experience in human subjects tests and EMPA offers a wide range of unique test apparatus, which have been partly developed in collaboration with the Swiss army [4]. This project gave a good possibility to combine the broad experience of both institutes in an optimal manner.

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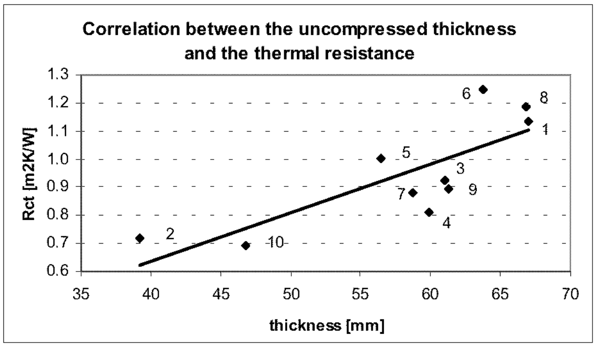
The series of tests and selections have been divided into three phases:
1: Material measurements of thickness and insulation (TNO and EMPA) for all 10 samples,
2: climatic chamber experiments of human subjects (TNO) for 6 samples selected after tests under point 1 and
3: tests with special test apparatus (thermal manikins) (EMPA) with all samples at different conditions;

No.	Filling material	weight [g]	thickness (at different pressures) in [mm]			thermal resistance [m^2K/W]	
			15 Pa	2000 Pa	1500 Pa	unstressed	at 2000 Pa
1	Synthetics	2624.5	67.0	6.9	10.9	1.133	0.178
2	Synthetics	2747.9	39.2	8.0	12.3	0.718	0.235
3	Synthetics	3116.8	61.0	9.0	12.4	0.923	0.240
4	Synthetics	2282.1	59.9	6.5	12.5	0.810	0.196
5	Downy feathered	1852.0	56.5	6.0	7.0	1.004	0.176
6	Downy feathered	1809.2	63.8	7.0	11.1	1.248	0.174
7	Synthetics	3462.0	58.7	7.0	11.0	0.882	0.200
8	Synthetics	2433.5	66.8	8.0	9.2	1.186	0.240
9	Synthetics	1956.5	61.3	8.0	15.1	0.895	0.230
10	Synthetics	2464.0	46.8	7.5	12.8	0.694	0.210

Table 1: details of the tested sleeping bags

Most of the tested sleeping bags had a nylon outer shell, a synthetic isolation fleece and a skin-friendly inner layer. Within the sleeping bags tested were also two bags containing down feathers (no. 5 and 6). Both the thickness assessment and the thermal resistance measurement have been performed uncompressed and at a pressure comparable to the human weight (between 1500 and 2000 Pa). Corresponding to the different heat transfer mechanisms the uncompressed thermal resistance was assessed with one calorimetric plate toward ambient air (close to ISO 11092) whereas at 2 kPa the measurement was carried out with two plates (ISO 5085-1).

The expectation that heavier sleeping bags would show less reduction of the insulation under a certain pressure could not be consequently proofed (table 1). But the down feathered bags lose more insulation capacity under pressure stress than their synthetic competitors. The thickness of the insulating layer is the most important factor for a high thermal resistance, followed by the volumetric weight and the surface properties (thermal resistance to the ambient air).



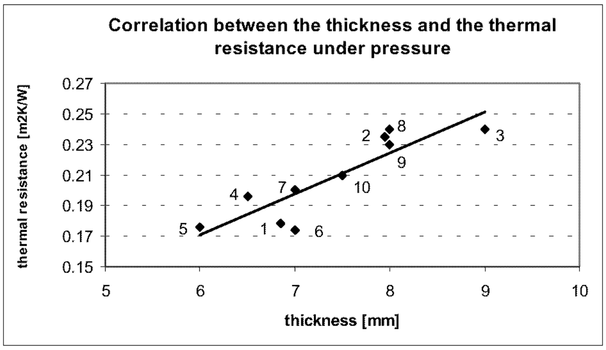


Figure 1: Correlation between the thickness and the thermal resistance at different pressures

In figure 1 it is clearly seen that some of the most voluminous sleeping bags lose most of their thermal insulation under pressure which can be explained by the low volume of material compared to the volume taken up in an uncompressed state.

Sleeping bags as a thermal system

To be able to judge the thermal properties of a sleeping bag in a practical manner the whole system consisting of human subject, clothing, sleeping bag, supporting layer, ground and ambient conditions have to be taken into account. The chosen place to sleep can play a crucial role protecting the sleeper from wind and foul weather. Furthermore it has to be considered that the thermal properties of a human and the environmental conditions can vary over a wide range. As well as the various other boundary conditions the manifold physical and psychological properties of different persons should be standardised for general considerations. This can be done by choosing specific human subjects and using a climatic chamber or by applying specialised apparatus under laboratory conditions.

Generally thermal loss can be classified according to physical criteria such as radiation, conduction and convection. Possible losses in sleeping bag systems include: conduction toward the ground, conductive and convective losses toward the sky, energy transfer through respiration and the influence of the evaporation of sweat. As mentioned above the sweat influences the thermal system mainly through the energy exchange for evaporation and condensation and the reduction of insulation due to replacement of insulation air by water. The evaporation extracts energy directly from the skin surface, whereas the re-condensation usually takes place in the outer layers. Unfortunately the reduction of insulation and the occurrence of condensation are interactive which makes it difficult to describe the system physically. The closer to the skin the evaporation or the condensation occur the larger the influence of these changes have on the skin temperature. The loss of energy due to evaporation is greater than the regain due to condensation since the latter usually occurs in outer textile layers and does not affect all of the moisture in the system.

Especially at low temperatures the respiration should not be neglected since the inhaled cold, dry air has to be moistened and warmed before it reaches the lungs. This process requires a lot of energy which will be lost with every breath. Under normal conditions the heat loss due to respiration is around 10%, at low temperatures it can be up to approximately 30% [1]. Reducing the breathing hole in the face region can lessen the loss of energy but causes more moisture to remain within the sleeping bag as well.

The design of the sleeping bag is very important, modern sleeping bags are equipped with an appropriate cover of the zipper and a thermal lock in the shoulder region. Without an appropriate underlay the thermal losses toward the ground are considerably higher than toward the sky. In an optimal system the heat loss toward the ground should balance the losses to the ambient air.

Measurements with the sweating Torso

The sweating Torso (figure 2) with its cylindrical shape was constructed to be similar to the human trunk. The individual layers of its surface have been chosen to simulate the thermal properties of the skin as closely as possible. In addition this apparatus can be filled with water to give a more realistic thermal capacity and behaviour for dynamic measurements. With 54 sweating nozzles the surface can be supplied with a defined amount of sweating water. Combined with the accurate temperature control, various work loads and recreation cycles can be simulated.

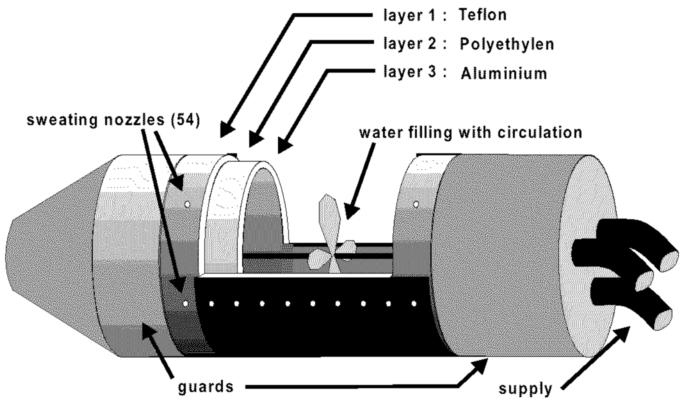


Figure 2: drawing of the sweating Torso

In this project a test program with two phases was defined, consisting of a two hour acclimatisation phase at 35° C without sweating and 8 hours to simulate sleeping with a constant heating power (85 W) and defined sweating (0.3 l/ 8 h). Although all sleeping bags had been acclimatised to the test environment before the test, phase 1 was used to determine the dry thermal insulation under realistic conditions and to guarantee a common starting point for all bags. During the tests the Torso was covered with an underwear (PES fleece) and the apparatus within the sleeping bag was put on a wooden board with a mattress on it. The whole system was positioned on a balance to register all changes in weight within a climatic chamber at –20° C. With this measurement system differences in the temperature course and the weight can be quantified between the 10 sleeping bags. Since the Torso does not have exactly the same thermal capacity and temperature control mechanism as a human body the results should be considered as relative.

In order to obtain more distinctive results the Torso was not filled with water in these tests. Without the water filling the thermal capacity is considerably reduced which lessens the practical relevance of the results in favour of emphasising the differences of the materials. To get results which can be compared to a certain extend with the human subjects tests some tests with water filling were executed.

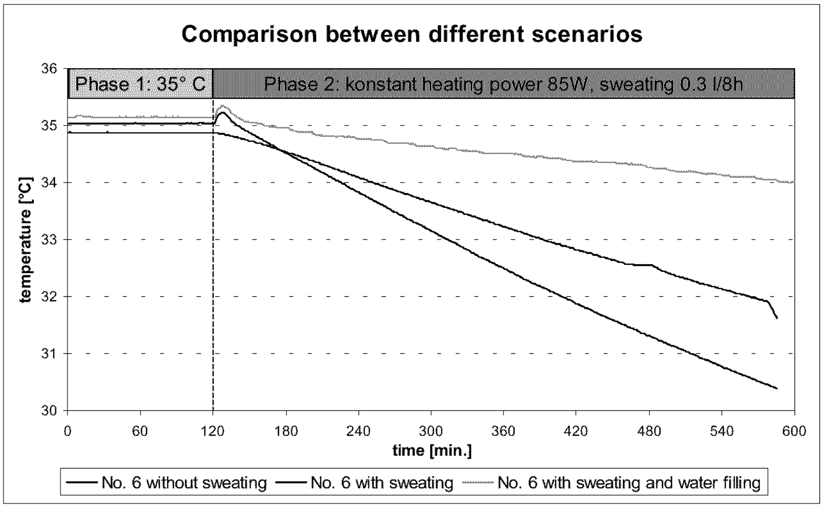


Figure 3: influence of different measurement scenarios on the temperature course

Figure 3 shows the results of the three different measurement scenarios where the effect of the additional thermal capacity can be seen as well as the influence of the small amount of sweat water used in this test. The temperature reduction was diminished due to the additional thermal capacity but still clearly measurable. In another assessment the same test was performed without sweating to demonstrate the influence of the released sweating water on the thermal insulation.

Torso measurement results
In these experiments it was found that at –20°C the Torso cooled down noticeably in all sleeping bags (figure 4).

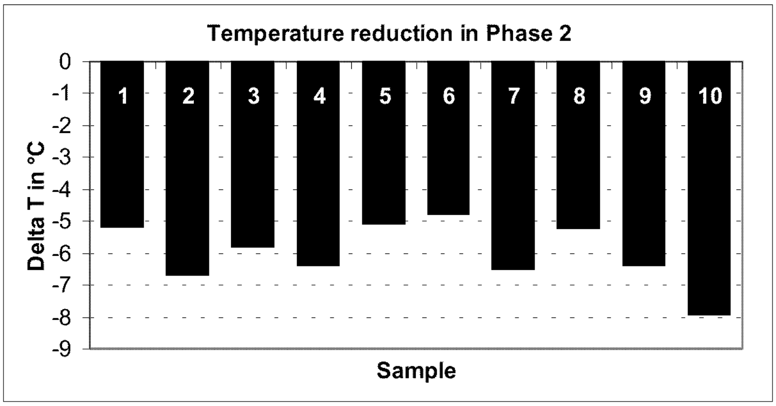
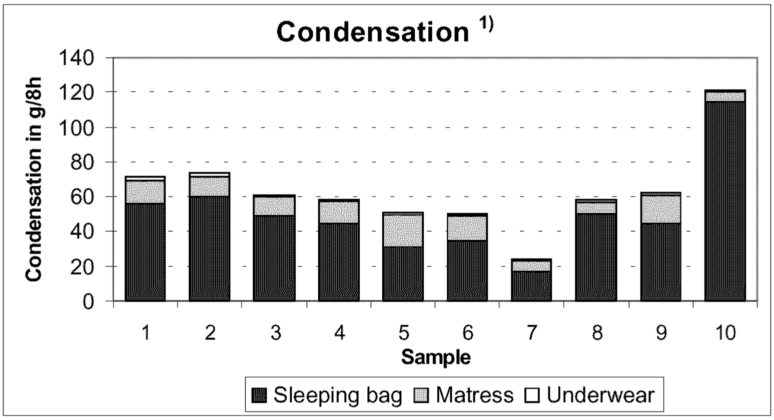


Figure 4: reduction of the surface temperature in phase 2

The measured temperature reduction between 4.8° C and 8.0° C appear to be rather high at first glance, but as the Torso was not filled with water, the results seem to be quite realistic and comparable with the human subject tests (see below). The ranking of the samples is more or less the same as that of the Rct values. Because of the dramatically reduced thermal resistance under pressure a worse result for sample 1, 5, 6 and 8 could have been expected. The matting and the wooden board seem to have compensated for the negative effect of the reduced thermal insulation.

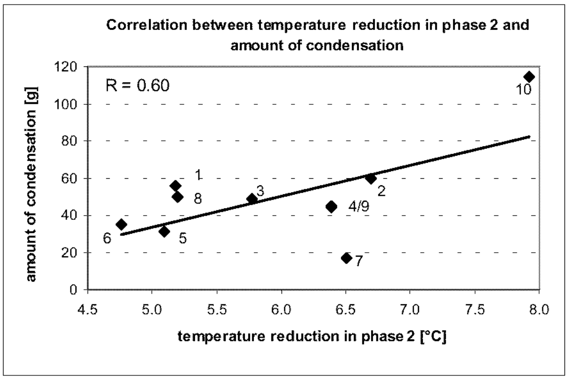
Condensation
Condensation of the vaporised sweat in a textile layer is provoked by the saturation of the partial water vapour pressure difference and is dependent on the temperature gradient between the body and the environment. A fraction of the energy given up by the evaporation can be recovered but at the same time the thermal resistance is negatively affected by the substitution of air with the condensed water.



1) The amount of condensation is related to the 160 g (20g/h) of totally released moisture in phase 2 of the measurement; the Torso represents only a part of the human body.

Figure 5: amount of condensation in the different layers

At moderate ambient temperatures (> 5° C) and the low sweat rates applied in this Torso measurement programme much less condensation would be expected. But low temperatures hinder evaporation and favour condensation. The measured quantity of condensation varies between 20g and 100g. The sleeping bag with the highest amount of condensation had the lowest thermal insulation. The weak correlation between the thermal insulation and the amount of condensation is shown in diagram 6 (R=0.7). Most of the condensation was found within the sleeping bag and approximately 20 to 30 % in the mattress as ice. In the underwear almost no condensation could be found. Except from sample 7 the down feathered bags (no. 5 and 6) showed the best results in this test.



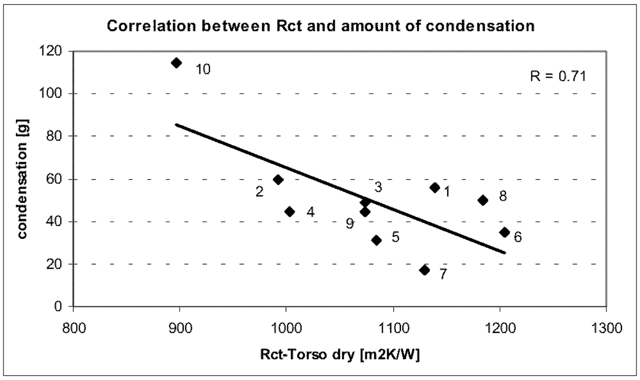


Figure 6: correlation between condensation and temperature reduction as well as the Rct measured on the Torso

Especially in the regions which are compressed the thermal insulation is reduced considerably under the influence of moisture. Measurements on different underwear materials showed that the heat transfer of wet materials is drastically increased depending on the amount of water present [2]. Also the Torso measurements showed a connection between the temperature reduction in the sweating phase, which is a measure for the reduced thermal insulation, and the absorption of moisture at the same time (figure 6).

Human subject tests

If the heat loss remains higher than the metabolic energy production over a longer period of time the temperature of the extremities will be reduced step by step. The vital organs such as the brain, heart and lungs have priority and remain at a high temperature level while the heat losses in the extremities can be reduced. By adapting the posture the quantity of heat loss can be influenced additionally. Laying on the side, slightly rolled up diminishes the contact area with the ground layers and pulling the arms and legs closer to the body reduces the active area for heat exchange with the environment simultaneously. The temperatures measured at the extremities are most suitable to judge the sleeping comfort because changes will be observed there first. Hands are less appropriate due to large movements and corresponding temperature changes. Whereas measurements on the toe or instep promise more accurate results. As soon as the heat loss gets too extensive the self regulative temperature control mechanism reduces the blood circulation which leads to a continuous decrease of the surface temperature at the toe or foot. As a reaction to the temperature reduction in the hands they will be pulled toward the body or placed on the chest which makes this information useless since the temperature on the chest decreases only if the temperature inside the sleeping bag has reached a very low level.

Based on the measurement of the thermal resistance and the thickness, six sleeping bags were selected for the climatic chamber experiments. Human subjects consisted of three men and three women to account for the dissimilar responses of the two sexes to cold environments. All the candidates were fit and between 20 and 30 years old. During six nights the sleeping bags were tested by all six people with temperature sensors on the hand, chest, upper leg and foot at an ambient temperature of –18°C. Besides measurements of the skin temperature, subjective ratings were collected on local and global comfort following every night and then analysed.

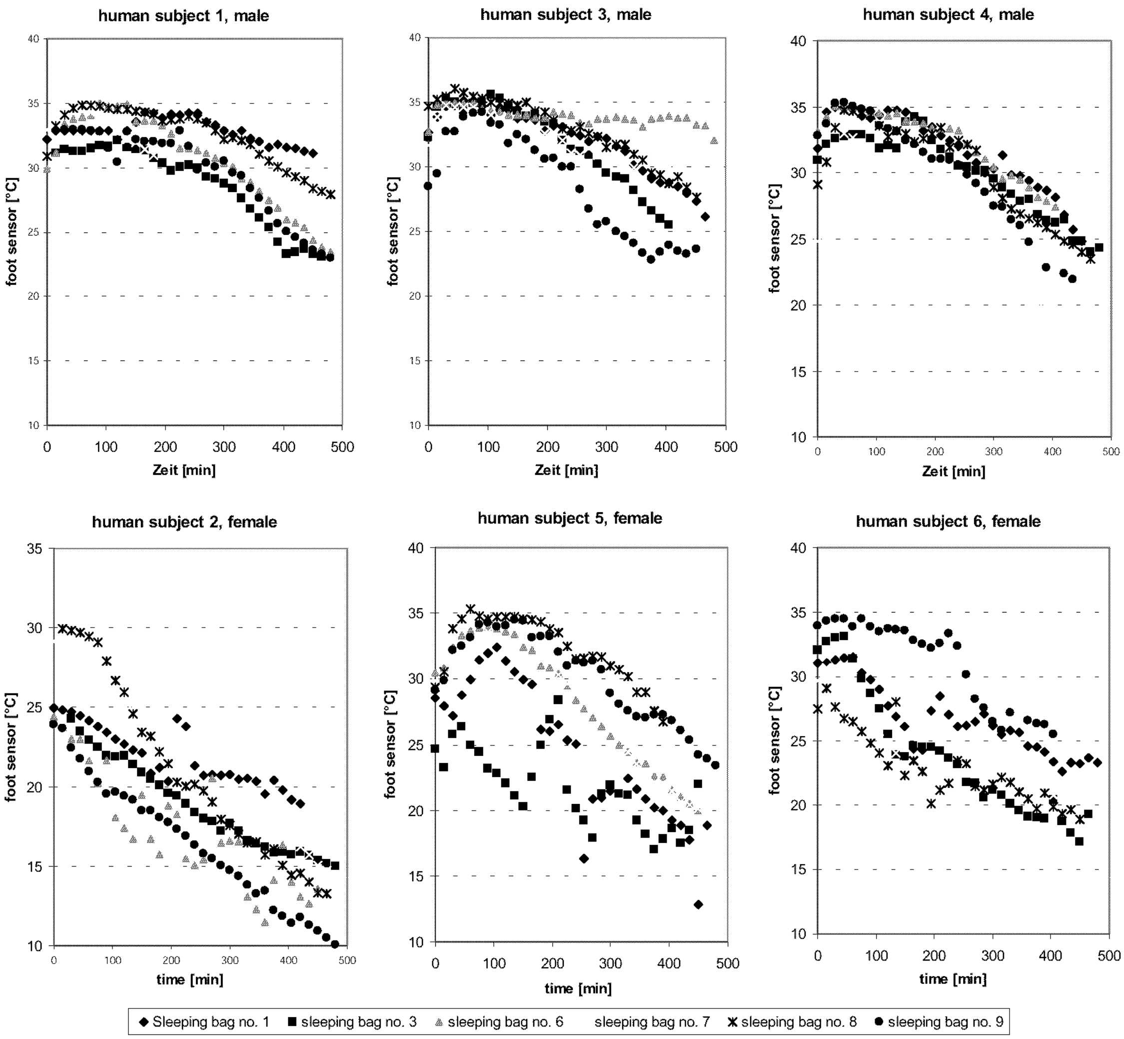


Figure 7: course of the measured foot temperatures

The graphs in figure 7 show the temperature course on the foot for all sleeping bags separately for each candidate. The scattering of the results for each candidate and sleeping bag can not be excluded totally in human subject tests and depends on the current physical and psychological condition of the subjects as well as the activities and meals during the day. For a more detailed analysis of the measured data additional measurements of the same human subjects with the same sleeping bags would be necessary.

Human test results

All subjects complained about cold or very cold feet which corresponds to the temperature courses shown in figure 7 and 8. On the other hand the temperatures measured with the other sensors showed no significant changes. There are noticeable differences between the results from male and female subjects, where particularly the foot temperatures of the female candidates are generally lower.

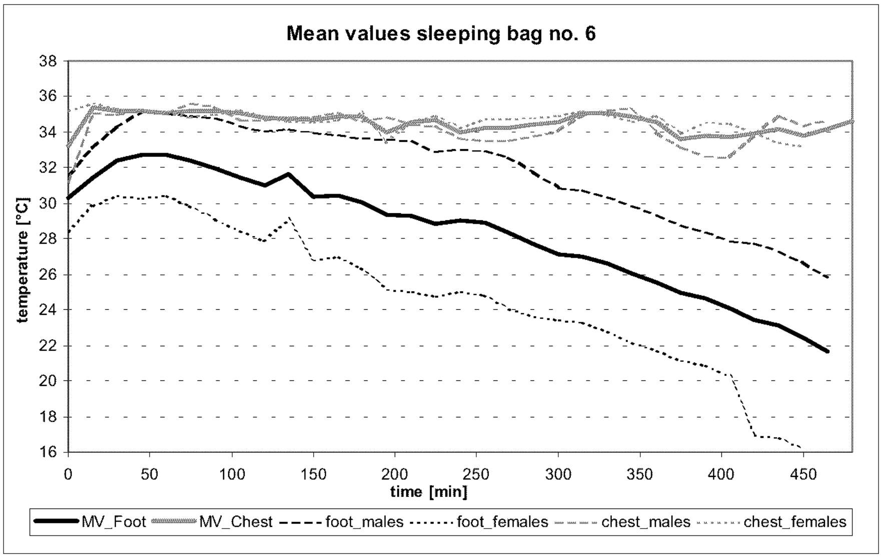


Figure 8: example of the temperature distribution of the foot and chest sensors

Figure 8 shows that for sleeping bag 6 the mean value of the measured chest temperatures remains around the start level, whereas the foot temperatures decrease significantly. The following table attempts to quantify the mean temperature reduction despite the relatively few data sets and the inherent scattering obtained. Relating to the foot temperatures, samples 1, 5 (especially with women) and 6 gave the best results.

No.	Temperature difference foot sensors			Temperature difference chest sensors		
	men	women	both	men	women	both
1	5.6	9.9	**6.8**	0.4	0.6	**0.5**
5	8.4	9.8	**9.9**	4.6	-0.3	**1.6**
6	4.5	10.7	**8.2**	0.2	-0.2	**0.6**
7	9.7	11.4	**10.8**	0.3	-0.1	**0.0**
8	6.3	13.5	**8.9**	-0.6	2.1	**0.8**
9	9.4	11.7	**9.9**	1.0	0.2	**0.3**

Table 2: mean temperature reduction of the foot and chest sensors

Comparison to Torso measurements

A direct quantitative comparison between the two investigations is not possible due to the slightly different boundary conditions and the insufficiencies of the Torso measurements mentioned. The ranking of the sleeping bags matches the measured temperature reductions quite well. Although the Torso was not filled with water and it only simulates the human trunk as well as the fact that the temperature reduction measured in the human subject tests was limited to the feet, the quantitative results show similarities.

Simulation and computer calculations

The range of use of sleeping bags is normally assessed with laboratory tests followed by computer calculations. The models utilised to calculate the limits of use are often based on rough simplifications which neglect the influence of sweating and condensation. A standardised calculation method according to a future European Standard could help solve this problem. The applied calculation models and methods should be accurate enough to allow sensible assessments of the minimal temperature of use.

A simple model used to estimate the lower limit of use

As a first approach the sleeping bag can be simplified to have only two different regions:

- An area on which the body lays where the bag and the underlay will be compressed
- An uncompressed area in contact with the air around the bag

In both cases an energy balance can be set up assuming adequate geometrical and thermal boundary conditions. Taking into consideration the metabolic heat production an estimate for the minimal temperature of use can be calculated. But even if this simple model will be expanded with additional regions between these two main areas some important types of heat loss are ignored. The heat loss due to respiration, where warm moist air is exhaled, and evaporation of sweating water are not included in the balance. Physical models which accurately reproduce these influences can only be realised with complicated computer simulations (see Sweat management project [2]).

Model according to prEN 13537

The proposed European Standard prEN 13537 uses a different method. With a thermal manikin wearing standardised clothes measurements are executed in a climatic chamber under defined conditions. The measured dry thermal resistance is taken as a basis for the calculation of the limit of use adding estimates for the influence of evaporation and respiration to the computer model. The standard calculates 4 different steps using parameters from a standard male and female person: extreme (assuming a person shivering with cold), limit, comfort and maximum temperature (with the zipper half way open). But even with this complex simulation model the results remain a estimate of the real limits. Unfortunately the manufacturers use the extreme temperature to promote their products. Compared with the results of this study the temperatures calculated for the comfort or limit range match quite well with the temperature region where comfortable sleep is possible.

Comparison of the two computer models

sleeping bag	thickness and thermal resistance only	According to EN 13537 based on Rct Torso	
		limit	extreme conditions
1	-8.9° C	-9.6	-27.8
2	-3.4° C	-4.3	-20.9
3	-9.6° C	-7.3	-24.8
4	-9.5° C	-4.7	-21.4
5	-1.8° C	-7.6	-25.3
6	-7.7° C	-12.0	-30.8
7	-7.4° C	-9.3	-27.4
8	-6.5° C	-11.2	-29.9
9	-12.9° C	-7.3	-24.8
10	-6.4° C	-0.8	-16.4

Table 3: calculated limits of use

An additional problem of this simple approximation comes from the complex temperature regulation processes of the human body. The temperatures of different regions of the body can vary markedly depending on the outside conditions. This problem could be partially alleviated by an anatomically shaped, heated manikin with thermal properties like a human and programmed to behave similar to a human. In fact it should not be neglected that the maximal temperature depends on the physical state of the sleeper as well as the additional equipment used and some other factors.

Conclusions

The corresponding results from the human subject test and the measurements on the sweating Torso seem to confirm that none of the tested sleeping bags can be comfortably used at temperatures below –20° C. Without an appropriate mattress the heat exchange to the ground is so high that at such low temperatures one can not sleep for more than a few hours before waking up with cold feet. It also became evident that not all filling materials had the same ability to transport moisture to the outside. The resulting condensation which was considerably higher in some of the samples could cause problems on longer expeditions when the sleeping bags can not be dried during the day.

In this project, the problem of computer calculated temperature limits could only be handled very briefly. The variety of different calculation methods and the sometimes too optimistic results make it necessary to find an accurate rating scheme as well as the mentioned proposal for a European standard. Some of the correlations found could be useful for the development of a simple computer model. The negative correlation between the dry thermal resistance and the temperature decrease in the second phase of the Torso measurement can be used for that purpose as well as the dependance between the quantity of condensation and the temperature reduction.

Concluding remarks

The examination of the influence of moisture and the interaction of combinations of textile layers show that a fundamental knowledge of the physics involved is essential for the understanding of these processes. Starting with the “Sweat Management” project [2] EMPA began to emphasis computer model calculations and simulations to enhance the knowledge on the complex physical connections. Particularly the effect of moisture is worth examining more closely since this is essential for successful research and development projects with manufacturers or co-operating institutes to find an optimal balance between comfort and safety. The newly built movable, sweating manikin SAM [8] could help to improve accurate tests on sleeping bags due to the reproducible, anatomically correct simulation of a human being.

In this study ageing and durability properties have been ignored. The thermal insulation characteristic is largely influenced by the ability to expand to the original volume following washing or transportation in a small bag. Particularly repetitive washing can reduce the insulation and therefore this aspect should be investigated in future projects. The sleeping bags examined in this study will be subjected to 5 washing machine cycles and tested again. In addition TNO will use some of these sleeping bags for a long period field trial.

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