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Moisture Accumulation in Sleeping Bags at Sub-Zero Temperature; Effect of Semipermeable and Impermeable Covers

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ABSTRACT

As sub-zero temperatures were expected to affect vapor resistance of microporous membranes, the effect of using semipermeable and impermeable rain covers for sleeping bags on the accumulation of moisture in the bags during 6 days of use at -7°C was investigated. Moisture accumulation was found to be related to the vapor resistance of the materials used. The best semipermeable material gave the same moisture buildup as no cover. It was concluded that semipermeable cover materials are effective in reducing moisture accumulation in sleeping bags at moderate sub-zero temperatures.

INTRODUCTION

In the use of sleeping bags in low temperatures, the accumulation of moisture in the bags over prolonged periods of use has been a major problem. This accumulated moisture causes a reduction in heat resistance due to the higher conductance of moisture compared to air and due to a constant evaporation/condensation cycle [7, 8] which takes place from the warmer (inner) to the cooler (outer) parts of the bag.

The source of the moisture are the users of the bag themselves, who may exhale warm moist air into the bag, and who lose moisture through their skin, as well as from any moist clothing or equipment they take into the bag. The water may then enter the bag by wicking from the clothing or by evaporation and condensation. At or close to the user's skin, the temperature will be high, which means moisture evaporates easily. As the environment is typically cool, with a low moisture content, a water vapor concentration gradient is present from the skin to the environment, and thus moisture will move in that direction. Because the temperature decreases from the skin to the environment, the maximum (saturation) water vapor concentration also decreased along this path. When it is cold outside, the temperature gradient through the insulation material may be steep enough that at many points the saturation concentration equals the actual concentration of water vapor in the insulating material. Where this is the case, water vapor will condense within the insulation of the sleeping bag.

This moisture accumulation takes place in all types of sleeping bags, but the extent of the phenomenon is, apart from the environmental temperature, expected to be highly dependent on the vapor permeability of the sleeping bag materials. Especially when sleeping bags are

used with rain protective covers the problem will increase dramatically as the vapor resistance of such covers is usually much higher than that of normal fabrics. In military applications or in expeditions, where airing of the sleeping bags on a regular basis is not possible, some of the problems with moisture accumulation (freezing while packed, loss of insulation [1], odor) can be life threatening

To minimize the problem, many manufacturers developed rain covers from waterproof, but vapor permeable materials (e.g. porous PU coatings or PTFE membranes with or without hydrophilic layers), to allow for optimal evaporation. The behavior of these materials has been studied under various circumstances as e.g. in different ambient humidities [2], with condensation at its surface [11], at various atmospheric pressures [4], and in various ambient temperatures [3]. Studies on the behavior of such materials at low temperature however have shown that the vapor resistance of some of these materials increases dramatically when temperatures fall below zero degrees Celsius [9, 10]. Further, when used in a thick sleeping bag, one can expect the vapor concentration gradient over the actual cover material to be quite small. The functionality of these materials in such conditions can therefore be questioned. What happens to the material's vapor resistance when water condenses at its surface and then freezes (or directly freezes from vapor) is yet unclear. In order to study these problems for their relevance for sleeping bags, an experiment was devised to test whether the use of semi-permeable versus impermeable rain covers for sleeping bags is effective in removing excess moisture in moderate cold. It is expected that conclusions from this research can also be used in other applications of these materials in such circumstances.

METHODS

Subjects: The physical characteristics of the subjects are presented in Table 1.

Sleeping bags: For the experiments mummy-type sleeping bags with identical synthetic batting insulation (including mattress: $0.93 \text{ m}^2\text{KW}^{-1}$, measured on the same human subjects using heat balance technique [5]) were used, differing only in the type of outer cover. Four conditions of outer cover were used (vapor resistances of covers (R_{cover}) given in brackets, measured according to [12] at 2 mm from wet surface):

A. no cover (reference condition: $R_{\text{cover}}=0$ mm of equivalent standard still air, ESSA),

- B. fixed impermeable cover (worst case; $R_{\text{cover}} > 300$ mm ESSA),
- C. fixed, full semipermeable¹ cover ($R_{\text{cover}} = 3.5$ mm ESSA),
- D. fixed, full semipermeable² cover ($R_{\text{cover}} = 7$ mm ESSA),

⁽¹⁾ = PTFE membrane with hydrophilic component, ⁽²⁾ = PU coating

Procedures: The bags were used in a climatic chamber, set at a temperature of -7 °C, wind of $0.2 \text{ m}\cdot\text{s}^{-1}$, relative humidity 40-50%. They were used on top of a 15 mm thick polyurethane mattress. The climatic chamber floor was of aluminum, with hollow space underneath that was controlled at the room temperature as well. The bags were used for six consecutive days, with 6 hours “sleep” per day. The bags were packed in impermeable plastic bags between use periods, to simulate field conditions, where no airing of the bags between uses is possible. The bags were stored at room temperature. Six subjects used the bags, with a daily rotation over bags to avoid subject effects. Before entering the bag, the subjects put on underwear and combat clothing. The latter was treated daily (dried and subsequently moistened), to contain a moisture amount of 150 grams when entering the bag. This was used to simulated moisture accumulation in the clothing due to daily activities (light sweating). Before and after each trial period, weights of the bags, clothing and subjects were obtained in order to determine the moisture balance. Subjects were asked to breathe outside the bag to avoid adding more moisture from respiration.

Subjects core (rectal) and skin temperatures (head, hand, arm, chest, back, leg, foot) were logged at 1 minute intervals. Twice during each session, metabolic rate was determined by measurement of oxygen uptake [5].

Statistical analyses were performed using repeated measures ANOVA, with a significance level of 0.05 as criterion.

Results and Discussion

Visual inspection of the sleeping bag covers immediately after each use showed that indeed moisture was present on the inside of the cover as well as hoar frost, though it was unclear whether the moisture was melted frost or present as liquid at the end of the session. This frost presence confirms that vapor transport at the cover took place at sub-zero temperatures. Based on the heat and vapor resistances of the bag, cover and air layer

surrounding the bag, the cover temperature can be estimated to have been between -2 and -4 °C.

Body temperatures and skin temperatures differed significantly between subjects, but did not show significant differences between bags. This should not be interpreted as that no effect of moisture accumulation is present. It is caused by the rotation of subjects over bags and the high variability between individuals. In order to analyze the effect of moisture accumulation on subject's physiological responses, the experiment would have needed a different design: all subjects using all bags for six days. This would have increased the size of the experiment six-fold, making it impractical. For the current analyses, only the moisture balance data were used. Moisture balance was less affected by subject variability than the skin and body temperatures. The results of the moisture balance are presented in Figure 1. In this figure the weight loss from the moistened clothing, which was measured daily, is presented cumulatively. This represents the minimal amount of moisture introduced into the sleeping bag. In reality more will be added due to insensible perspiration through the subject's skin. This is estimated, considering the vapor gradient at the skin to the cool moist clothing, at around 70 to 100 g per session, but is the same in all bags. Being a constant factor, this was left out of the graphs.

Also in figure 1, the weight increase of the sleeping bag is presented. This reflects the amount of moisture that does not leave the sleeping bag through openings, or through the covers.

From this figure, following the time course of the moisture accumulation and evaporation over the six days, it is clear that the amount of moisture evaporating from the clothing is roughly identical for all cases (differences are not significant). The amount staying within the sleeping bag is very different though. In the no cover condition -A- the accumulation is minimal. In the impermeable cover condition -B- it is almost equal to the amount evaporated from the clothing, consistent with the expectation for the type of material.

Figure 1 about here

Of the two semi-permeable covers, the one made from PTFE material -C- shows only minimal moisture accumulation, which does not seem different from that without a cover.

The other semi-permeable cover -D-, with a polyurethane based coating, reduces moisture accumulation compared to the impermeable cover, but does not perform as well as the PTFE based cover. Based on the higher vapor resistance for this specific PU cover, a difference was expected. However, as the total vapor resistance of bags + cover is relatively close due to the high vapor resistance of the thick bag (~ 50 mm ESSA), the observed difference is higher than expected based on room temperature vapor resistances alone. Whether this is due to the low temperature or to some effect of frost or ice on the vapor resistance of this material is unknown, but the PU coated cover seems more affected by the experimental conditions than the PTFE cover.

The overall results for the conditions are brought together in Figure 2, which presents the total amounts of moisture accumulated in the bags after 6 days, and compares it to the average total amount of moisture evaporated from the clothing.

Based on the data on increases in vapor resistances of the hydrophilic component in PTFE membranes [9, 10], the resistance of that layer was expected to increase by a factor of 3 to 4 at the temperature of around -3°C of the membranes in the current experiment. This would imply an almost doubling of the total resistance of the complete PTFE material. Given the moisture load used (250 to 280 grams per 6-hour sleep period), this apparently did not cause substantial moisture buildup in the bags for these materials. For the application of Dutch army bags (the background of this research), the conditions used can be regarded as representative for cold periods, especially when tents are used. As vapor resistance increases further at temperatures lower than this, it may be worthwhile to repeat the test at lower temperatures when considering for example arctic applications.

Figure 2, about here

Conclusions

The results show that using an impermeable, non-detachable cover around a sleeping bag at sub-zero temperatures will lead to excessive moisture accumulation over a period of days. It was observed that using a semi-permeable membrane was beneficial in terms of a reduced moisture accumulation in the tested climatic conditions (-7°C). Of the tested semi-

permeable covers, the worst performing still reduced moisture accumulation by half. The best material did show a similar performance to the condition without a cover. The differences between the two semipermeable materials (PTFE based and PU coating) were higher than expected based on the materials vapor resistances at room temperature. The PU coated cover seems more affected by the experimental conditions than the PTFE cover. To explain this observation may require further research. It is expected that conclusions from this research can also be used in other applications of these materials in such circumstances (for example ski-wear).

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Table 1, Physical characteristics of the subjects

Subject	Height (m)	Mass (kg)	Body surface area (m ²)	Fat content (%)
1	1.84	75	1.97	15.2
2	1.80	73	1.92	14.7
3	1.95	72	2.02	10.0
4	1.77	68	1.84	9.2
5	1.82	74	1.95	13.7
6	1.92	69	1.96	8.7

Figure 1 , cumulative weight change over six days of use of sleeping bags and cumulative weight change of clothing worn, for different sleeping bag covers. ¹=PTFE membrane cover with hydrophilic layer; ²=polyurethane coating.

Figure 2, total cumulative amount of moisture evaporated from the clothing over the six days of sleeping bag use, compared to the total amount of moisture accumulated in the bags over the same period. ¹=PTFE membrane cover with hydrophilic layer; ²=polyurethane coating



