

The Influence of Sweating on the Heat Transmission Properties of Cold Protective Clothing Studied With a Sweating Thermal Manikin

Harriet Meinander

SmartWearLab, Tampere University of Technology, Tampere, Finland

Mari Hellsten

VTT Processes, Finland

One of the objectives of the European SUBZERO project was to study the influence of sweat evaporation and condensation on the heat transmission properties of cold protective clothing. With the sweating thermal manikin Coppelius, water vapour transfer through and water condensation in the clothing can be determined simultaneously with the thermal insulation. In this study, 4 cold protective ensembles, intended for use temperatures between 0 and –50 °C, were measured with the dry manikin and at 2 different sweating rates. In addition, the ensembles were measured with non-sweating thermal manikins and in wear trials.

protective clothing cold protection thermal manikin sweating

1. INTRODUCTION

Cold protective clothing with high thermal insulation is needed both in outdoor winter conditions, particularly in the arctic and subarctic regions, and in artificially cooled cold stores. The most important property of cold protective clothing is an appropriate thermal insulation value, which corresponds to the expected thermal environment and the level of physical activity. According to the European prestandard ENV 342:1998 [1], the assessment of thermal insulation is done with a movable thermal manikin, and the value is marked on the garments.

For thermal comfort in the cold, the water vapour transmission properties of the clothing are almost as important as thermal resistance.

There are many situations where perspiration starts in order to increase the heat loss from the body, and moisture in the clothing is particularly problematic in cold environments. According to ENV 342:1998 [1], water vapour resistance R_{et} of the clothing material is determined with the “skin model” method, EN 31092:1993 [2]. Water vapour resistance is inversely related to water vapour permeability or “breathability”.

The measurement according to EN 31092:1993 [2] is done in isothermal conditions at 35 °C without moisture condensation in the samples. In most wear situations there is however a temperature gradient through the clothing layers, which leads to an increased water vapour resistance, increased absorption and decreased wear

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Correspondence and requests for offprints should be sent to Harriet Meinander, Tampere University of Technology, SmartWearLab, Sinitaival 6, FIN-33720 Tampere, Finland. E-mail: <Harriet.Meinander@tut.fi>.

comfort. Several authors have shown that a decreasing environment temperature leads to drastic changes in the measured thermal properties of textile material combinations [3, 4]. Clothing for subzero conditions should therefore, if possible, be measured in temperatures which correspond to the intended wear conditions, to estimate moisture resistance properties.

For the estimation of water vapour transmission and the total (dry and evaporative) heat loss from a clothed body, a sweating thermal manikin can be used. With a sweating thermal manikin, the water vapour transfer through the clothing is determined simultaneously with thermal insulation. The changes in thermal insulation due to condensation of water in the clothing can be studied as a function of perspiration level and environmental temperature.

The European SUBZERO project was performed by a consortium of seven leading clothing physiology research institutes and five clothing manufacturers to provide data for the revision of ENV 342:1998 [1]. The objective of the project was to define the following important facts concerning thermal manikin measurements on cold protective clothing:

- the reproducibility of the thermal insulation test results, measured in accordance with the method referred to in ENV 342:1998 [1], using different types of thermal manikins (shell material, size, number of separately heated body segments, movement mechanism, dimensions);
- the relationship between physically measured thermal insulation values of cold protective clothing and the corresponding physiological reactions on human test subjects;
- the influence of sweat evaporation and condensation on heat transmission properties;

- the influence of ambient conditions on the thermal insulation value;
- to compile a database containing information on the thermal protection properties of cold protective clothing.

The project has been reported in Meinander et al. [5]. This paper deals with the third item, the quantitative influence of sweating on heat loss and thermal insulation, as well as water vapour transmission through the clothing under different conditions.

2. METHODS

The sweating thermal manikin Coppelius was used for this part of the SUBZERO project. The sweating manikin simulates the heat and moisture production of the human body and measures the influence of clothing in different environment and sweating conditions. A description of the manikin is given in, e.g., Meinander [6]. The manikin, which is divided into 18 heated zones, is heated to a defined surface temperature (34 °C). A defined amount of liquid water is supplied to the 187 sweat glands under the surface, where it evaporates. The heat loss from the manikin's surface and the weight increase of the total system (manikin + garments) are recorded during the test, and the amounts of water absorbed in each garment are defined after the test.

Four clothing ensembles were chosen from the participating garment manufacturers' catalogues to give adequate protection in the temperature range from 0 to -50 °C. The ensembles consisted of two or three layers, and are described in Table 1. The outer garments were tested in two versions, with and without a watertight breathable barrier.

The ensembles were tested at two sweating levels: 100 g·m⁻²·hr⁻¹ and 200 g·m⁻²·hr⁻¹. In addition, measurements were done with the dry

TABLE 1. Test Ensembles and Intended Temperatures

Garment		Environment temperature			
		0 °C	-10 °C	-25 °C	-50 °C *
		Ensemble A (1)	Ensemble B (2)	Ensemble C (3)	Ensemble D (4)
Underwear	1	×	×		
	2			×	×
Intermediate B			×	×	×
Outer garment	1	×	×		
	2			×	
	3				×
Footwear	1	×			
	2		×	×	×
Socks	1	×	×	×	×
	2			×	×
Handwear	1	×			×
	2		×	×	×
Headgear	1	×	×		
	2			×	×
	3				×

Notes. *—The equivalent temperature of -50 °C was achieved through a combination of low temperature and wind (-40 °C/3 m/s and -23 °C/10 m/s) in the wearer trials.

manikin, without sweating. The manikin was operated only in a standing position as walking is not possible. The ambient air temperatures were 0, -10, -25 and -50 °C, respectively, i.e., the temperatures for which the ensembles were intended and at which corresponding wearer trials with human subjects were performed. The duration of a sweating test was 3 hrs. In the end the conditions were close to steady-state, i.e., there was no or only minor increase in the condensation and heat supply values. The values for evaporation rate and power input were averaged from the last 10 min. Two repetitions of each test were done, and the difference between the results was less than 10%.

Corresponding wearer trials with human subjects were done in order to validate the manikin results against practice. The same garments were tested in similar environment conditions at two activity levels: moderate activity to keep the subjects at thermal comfort

without sweating and high activity at 50 W/m² higher metabolism to generate considerably more sweat to maintain thermal balance. This was achieved by choosing the treadmill walking speeds and inclination. Detailed description of the wearer trials and other project results are given in Meinander [3].

3. RESULTS

The measured heat losses through the clothing ensembles are shown in Figure 1. The total heat loss is divided into a dry (H_{dry}) and an evaporative (H_{evap}) part, where the evaporative heat loss is calculated from the amount of water vapour transmission.

The increase in total heat loss with increasing sweating is due to two reasons: evaporative heat loss and wetting of the clothing. In the higher temperatures (ensemble 1 and 2), sweating is relatively efficient and the

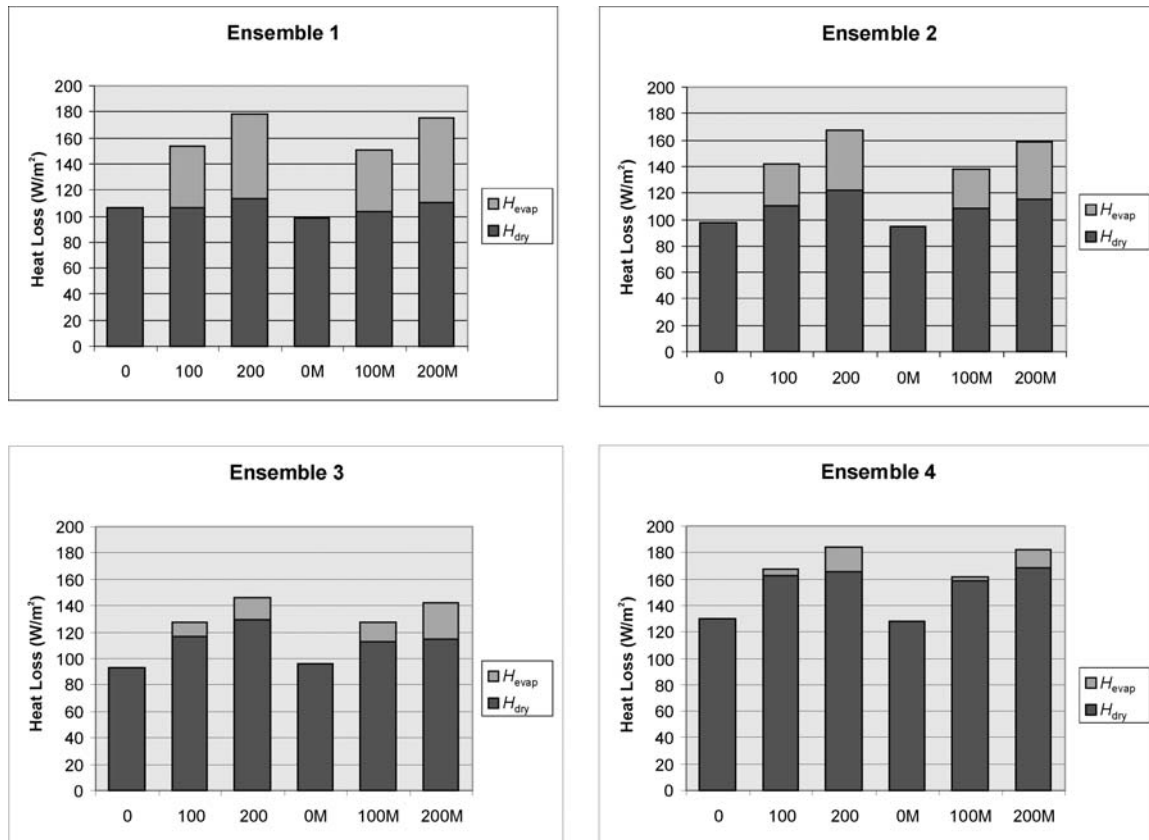


Figure 1. Heat loss through the four clothing ensembles (without and with membrane) at different sweating levels, measured in the respective ambient temperatures. Notes. H_{evap} —evaporative heat loss, H_{dry} —dry heat loss.

evaporative heat loss substantial, whereas wetting of the clothing causes more increase in the total heat loss in the lower temperatures (ensembles 3 and 4).

No systematic differences between ensembles without and with watertight membranes could be shown.

The accumulation of water in the garments increases with an increasing sweating level and with a decreasing temperature, shown in Figure 2. The largest amount of water was in all cases measured in the outer layer, where ice was also noted at very low temperatures. The underwear in ensembles 1 and 2 is a thin

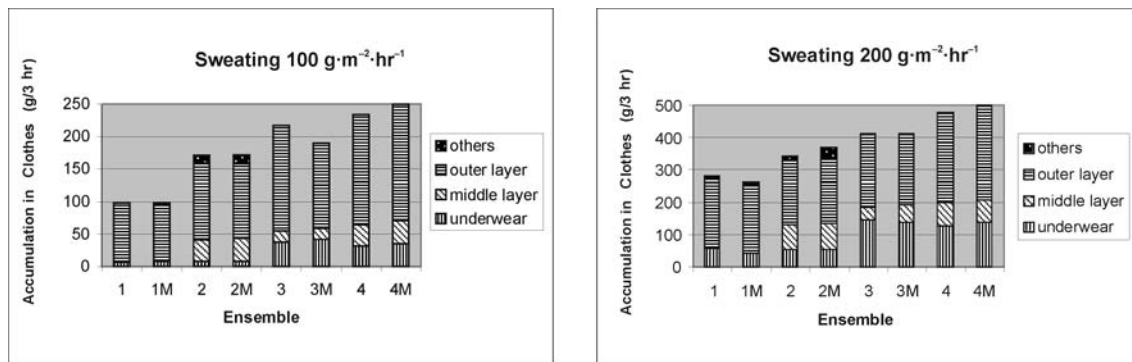


Figure 2. Accumulation of water in the clothing during the tests at 100 and 200 $\text{g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$ (NB: different scales of the figures).

polypropylene knit, which at the lower sweating rate does not absorb much water. In ensembles 3 and 4 the underwear is a thick woolrich knit, and the absorbed amounts of water are higher. The middle layer is a thick polyester fleece knit, which seems to absorb more from the thin synthetic than from the thick wool underwear.

The total water supply to the sweating surface was 425 g/3 hr at the lower and 849 g/3 hr at the higher sweating level. The efficiency of the sweating can be expressed as the ratio between evaporated and supplied moisture. In the best case, ensemble 1 with membrane at lower sweating the value is 60%, whereas in the worst case, ensemble 3 at higher sweating it is only 12%.

When comparing the sweating thermal manikin values with the corresponding results from the physiological tests a couple of differences in the tests have to be noted:

- the sweating manikin was standing whereas the test persons were walking on a treadmill;
- the amounts of sweating in the physiological tests varied considerably between test persons, and were higher than planned particularly at the very low temperatures;

- the physiological tests on ensemble 4 were performed in a combination of low temperature and wind.

Figure 3 shows a comparison between the evaporative water transmission values through the ensembles, measured with the sweating manikin at the two sweating levels and on the test persons at the two activity levels. The values are given as the evaporated fraction of submitted/produced water. The correlation between the manikin and test person results is good, considering the differences in test conditions. The proportion of evaporation decreases with an increasing thickness of the clothing and a decreasing temperature. Again, no big differences can be noted between ensembles with and without a membrane.

In the sweating manikin tests, the higher sweating level generally shows a lower percentage evaporation value than the lower sweating level, but in the wear trials the difference is in most cases reversed. This is probably due to the fact that the test persons were walking and thus increasing the ventilation in the clothing whereas the manikin was standing.

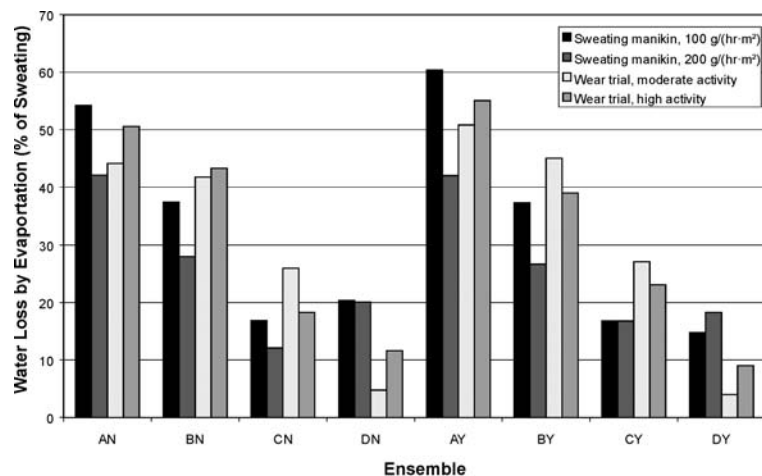


Figure 3. Average evaporative water loss through the clothing ensembles during sweating manikin tests and wearer trials. Notes. N—without, Y—with membrane.

4. DISCUSSION

Moisture in cold protective clothing can cause problems. The sweating or evaporative cooling starts when the dry heat loss from the body is too low compared to the heat production, and the ideal situation is that the produced sweat is transmitted as water vapour through the clothing to the environment, thus also transmitting the excess heat from the body. When the temperature drops, the uptake of moisture in the air however decreases, and the water vapour transmission through the clothing becomes less efficient. Instead, the produced moisture is absorbed by the clothing, where it causes a decrease in thermal insulation and discomfort. Particularly in situations with alternating high and low physical activities in cold environments, where sweating results in wet clothing at high activity and high thermal insulation is needed in the low activity, the decrease in thermal insulation due to moisture in the clothing might be a serious problem.

Therefore it is important that the influence of sweating on the properties of cold protection clothing is understood and considered when choosing clothing for particular activities in the cold. According to ENV 342:1998 [1], the water vapour permeability of the clothing materials is measured using the sweating guarded-hotplate test [2]. This however does not consider the changes in moisture transmission due to changes in environment temperature. Rossi et al. have recently shown with measurements on a sweating arm that the effective water vapour resistance and the moisture accumulation rate of four-layer textile combinations decrease almost exponentially when the environment temperature is raised from +1 to +20 °C [4]. Meinander showed similar tendencies in a study on different material combinations for cold protective clothing, measured with a sweating cylinder in temperatures of 0, -20 and -40 °C [3].

Physiological wear trials or simulations with sweating thermal manikins in a realistic wear environment can show the influence of moisture on the thermal properties of cold protective clothing. Physiological wear trials with human test subjects are expensive to perform and the individual differences between the test persons lead to a large variance between the individual results. Physical tests with the sweating thermal manikin, which simulates the simultaneous heat and moisture production of a human, are controlled and systematic test series under defined conditions can be performed. A limiting factor with the sweating manikin is that ventilation through walking cannot be simulated.

The results of the SUBZERO project showed that the effect of sweating on the thermal comfort properties of cold protective clothing can be reliably determined with the sweating manikin. The effects of movement ventilation and wind have to be estimated through correction factors.

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