Clothing thermal evaluation using heat balance techniques

Wouter A. Lotens
TNO-Institute for Perception
Soesterberg, the Netherlands

The heat balance

Since many years the well known heat balance technique is used to determine the heat resistance of clothing. Human subjects are used as a heat and vapour source and the *dry* heat loss is calculated as: Dry = M - Wext - Resp - Evap - Sto. This is called partitional calorimetry (1) and the partition that is called Dry is calculated because it is the only one *that* is not so easily measured directly. The heat resistance is calculated from *Dry* and the temperature gradient For Sto a weighted sum of internal and skin temperature is taken. The weighting depends on the blood distribution over the body. In the heat the weighting of the skin should be .1. Farnworth and Havenith (2) showed that in the cold the weighting should be higher than the usual 33. In any case the accuracy of Dry can be improved by waiting for equilibrium so that Sto is small.

The heat balance might he used to determine heat and vapour resistance at the same time, but this also goes at the expense of accuracy since the relative error in Dry will increase with increasing Evap and the other way around. Also the variability in sweat production within and between subjects is a problem. The complications in the measurement of skin wetness and the statistically required large number of measurements lead Lotens and Havenith to an alternative method. To optimize Dry, Evap is excluded by wrapping subjects in plastic foil (3). Vapour transfer is measured with a tracer gas instead of water vapour (4). The advantages are that *Dry* is determined more accurate and that a vapour resistance measurement is taken some factor of 20 faster and reproduces better.

Interaction between heat and moisture

The above method has its limitations. Absorption or condensation of moisture in the clothing may occur. In such conditions only water vapour gives realistic results. This might be real sweat or water vapour from a wetted liner, wom over plastic covered skin. It becomes important then where the heat balance is measured. When moisture is absorbed in the clothing less moisture leaves the clothing compared to the skin, while due to liberated heat of absorption more *dry* heat leaves. The heat balance at the skin thus may he different from that at other locations. Usually Evap is determined by weighing subject plus clothing. It thus holds for the total system and the heat balance is taken for an imaginary envelope around the system. This should be done for the other terms of the heat balance as well. In particular for Sto the heat storage in the clothing is often neglected. For thermal stress and discomfort ratings the heat balance at the skin is more relevant then that outside the system. This heat balance is difficult to measure directly and if the heat balance at the outside is taken instead, it is absolutely neccessary to wait for equilibrium, when the two converge. Absorption processes may take a long time to complete. The estimated response time is 100/hcl min per 100 g/m2 of absorption capacity of the clothing (hcl = heat transfer coefficient in W/m2C) (5) and at least 3 response times should be waited after stabilization of the skin and environmental condition. The place where the heat balance is takens is also critical for the determination of heat and vapour resistances. It becomes even more pressing with condensation. The clothing surface will show an increased temperature due to liberated heat of condensation and few vapour will escape. In experiments the heat resistance of an impermeable garment varied over a factor of three depending on the rate of condensation *(6).*

Radiation

Radiation causes problems with the correct calculation of the heat production term in the heat balance, which comprises of metabolic heat and the absorbed part of the radiation. Metabolic heat flows from skin to clothing surface, whereas from that surface to the air both metabolic and radiant heat flow. Thus the determination of the intrinsic clothing insulation and of the *air* insulation should be based on different heat flows (7). Calculation of total insulation is not meaningful then. When radiation penetrates into the clothing the situation becomes complicated.

Motion, wind, and nude skin

Clothing is basicly irrelevant material that creates still air layers. The heat and vapour resistance for standing persons in quiet *air* can be calculated from the geometry of the clothing without knowledge of the materials (8,9). When the air is moved, heat and vapour resistance decrease due to internal circulation, ventilation, and reduced adjacent air layer. The decrease is more or less typical for all clothing, depending on posture, wind, activity and thickness (9). *An* exception is impermeable clothing. The vapour resistance of this type of clothing is strongly dependent on the ventilation, which cannot compete with vapour permeability, and certainly not with air permeability (10). For the intrinsic heat and vapour resistance also the exposed skin parts may play a large role, particularly for thick or vapour barrier clothing, when these become a major avenue of heat

4-Layer model of clothing

Most of the above phenomena are quantitatively described by a mathematical model for clothing ensembles which comprise of underclothing, trapped air, outer clothing, and adjacent air layer. No distinction is made between one *or* more layers of underclothing. Ventilation through apertures is taken into account. When the clothing properties are specified, for any boundary condition the heat and vapour gradients, the flows, and the resistances can he calculated. This model was evaluated by means of heat balance techniques for the effects of (transient) moisture absorption (5), condensation (6), semipermeability (11), heat radation (7), and ventilation (10). The 4-layer concept proved succesful in the quantitative description of dry and evaporative heat transfer. Currently it is being interfaced with the Gagge 2-node thermoregulatory model (12) to obtain a comfort and thermal stress evaluation tool that only requires *easy* to obtain input data. Such a model will provide more detailed information on physiological strain of clothed humans than can be derived directly from the heat balance (e.g. required sweat rate, 13). It also allows the calculation of subjective comfort or thermal stress ratings, using their physiological correlates.

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