Thermal Aspects of Vehicle Comfort

Ingvar Holmér¹⁾, Håkan Nilsson¹⁾, Mats Bohm²⁾ and Olle Norén²⁾

1) National Institute of Occupational Health

2) Institute of Agricultural Engineering

Abstract. The combined thermal effects of convection, radiation and conduction in a vehicle compartment need special measuring equipment accounting for spatial and temporal variations in the driver space. The most sophisticated equipment measures local heat fluxes at defined spots or areas of a man-shaped manikin. Manikin segment heat fluxes have been measured in a variety of vehicle climatic conditions (heat, cold, solar radiation etc.) and compared with thermal sensation votes and physiological responses of subjects exposed to the same conditions. High correlation was found for segment fluxes and mean thermal vote (MTV) of subjects for the same body segments. By calibrating the manikin under homogenous, wind still conditions, heat fluxes could be converted (and normalised) to an equivalent homogenous temperature (EHT). Regression of MTV-values on EHT-values was used as basis for the derivation of a comfort profile, specifying acceptable temperature ranges for 19 different body segments. The method has been used for assessment of the thermal climate in trucks and crane cabins in winter and summer conditions. The possibility for spatial resolution of thermal influences (e.g. by solar radiation or convection currents) appeared to be very useful in the analysis of system performance. Ventilation of driver's seats is a technical solution to reducing insulation of thigh, seat and back areas of the body. Constructions, however, may vary in efficiency. In one system seat ventilation allowed for almost 2 °C higher ambient conditions for unchanged general thermal sensation, in addition to the pronounced local effect. In a recent study the effects of various technical measures related to cabin design and HVAC-systems have been investigated. Quantitative data on the effects of for example heated windows, heated floor, air outlet positions and solar screens have been obtained.

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Introduction

Thermal comfort is one ultimate goal of heating, ventilation and air-conditioning systems for buildings as well as vehicles. It is also an important condition for the preservation of an optimal performance and a safe behaviour of the driver (Mackie et al., 1974; Norin et al., 1992). Assessment of the thermal environment in a vehicle is difficult due to the complex interaction of the HVAC-system with the vehicle compartment and the external, environmental factors (e.g. solar radiation, air temperature and wind speed). Thermal sensation votes given by panels of subjects are indicative, but not detailed enough to be conclusive in terms of system specifications (Rohles et al., 1979). Also, panels are expensive, time consuming and impossible to standardize. Discrete measurements of temperatures in the vehicle space are cheap, repeatable and commonly practised. However, measurements do not account for the independent effects of convection and radiation, as different types of sensors are required for their determination. So far there is no convincing theory, how to interpret results and predict driver's reaction.

The combined thermal effects of convection, radiation and conduction need more sophisticated measuring equipment accounting for spatial and temporal variations as well. Different approaches to the solution of the problem have been taken. Sensors measuring operative or equivalent temperatures have been developed and used for this purpose (Olesen, 1992). The use of a dummy equipped with numerous heat flux sensors represent another useful technique (Della Rolle et al., 1992). An elaborated version of this technique, uses a full-size, man-shaped manikin completely covered by "sensors", in order to measure in a realistic way the heat exchange over the whole body surface (Bohm et al., 1990; Madsen et al., 1986; Wyon et al., 1985; Wyon, 1989). The "sensors" are built into the "skin" of the manikin and measures local heat fluxes of defined areas of the surface.

Thermal comfort

Thermal comfort is by definition a subjective sensation. However, the use of standardised scales for collection of ratings of thermal sensation for large groups of individuals, has enabled researchers to define the essential components of the thermal environment and their interaction in determining the average response of the population. The result is available as a standard method (ISO-7730 1991).

Thermal comfort requires the maintenance of

- whole body heat balance
- local heat balance of parts of the body, for example head, neck and feet.

Heat balance must be maintained within certain limits of physiological strain (e.g. skin temperature and sweating).

Whole body heat balance is determined by the conditions for dissipating sufficient amounts of produced body heat to maintain an optimal and unchanged core temperature. Ambient climatic factors (air temperature, mean radiant temperature, humidity and air velocity) and clothing heat transfer properties set the limits for heat exchange.

Local heat balance, similarly, is determined by the local climatic and clothing conditions. The preservation of a "comfortable" local skin temperature is the essential component. In the vehicle compartment the first requirement is easy to fulfil. The physical activity of the driver and the associated body heat production, is normally low. Modern HVAC systems are powerful enough to provide sufficient heat in the cold season and cooling in the hot season, to ensure an optimal whole body heat balance.

However, the specific presumptions for a confined vehicle compartment, entail great compromises in terms of design. The result, also with modern equipment, is the creation of thermal asymmetries. They are largely an effect of the mismatch between the overall heating and cooling requirement and the requirement for a homogenous climate over the body surface.

For engineering purposes the "comfort" sensation has to be converted to and expressed in measurable, physical quantities. This can be done with the above mentioned ISO-standard with reasonable accuracy for relatively homogenous, indoor environments. In the vehicle cabin the climate is far from uniform and considerable local thermal effects must be considered and evaluated.

Comfort and heat loss

A person at rest produces approximately 100 W of heat ($\approx 60 \text{ W/m}^2$ body surface area). If clothing and ambient conditions are suitable the same amount of heat is lost

to the environment, most of it by convection and radiation (dry heat loss). Whole body heat balance is adequate and the person feels thermally neutral (neither warm nor cold). With increasing ambient temperature convection and radiation diminish. Sweat evaporation has to compensate for this in order to balance the heat production of 100 W. Sweating is associated with a sensation of warmth and discomfort.

In a cooler environment, convection and radiation increase, making total heat losses greater than 100 W. The physiological response is to reduce skin and extremity blood flow in order to lower the external temperature gradient. In this case the person feels cool or cold and uncomfortable. Another, normal response is to add more clothing.

In other words, for comfortable climatic conditions the dry heat loss can only vary within a certain narrow interval. In a similar way the heat balance of a skin segment can be analysed. Only for a certain narrow range of convective and radiative (and conductive!) heat losses, an optimal local heat balance and a "comfortable" skin temperature are maintained. Higher local heat losses will be felt as cool or cold and lower local heat losses as warm.

In other words, a detailed mapping of the relation between thermal sensation and the local heat flux, may provide useful conversion factors for expressing comfort in a measurable quantity.

Measurements of heat flow with a manikin

A man-sized dummy with the whole surface area heated in numerous, independently controlled segments provides a useful instrument for the measurement of whole body as well as local heat fluxes. Several such manikins are in laboratory use (Elnäs, 1988; Holmér et al., 1992; Madsen et al., 1986; Matsuunaga et al., 1993; Mayer et al., 1993; Wyon et al., 1989). They are also used by automobile manufacturers, e.g. Volvo, Mercedes, Renault and Isuzu. A few models are commercially available (Elnäs, 1988; Madsen, 1993).

In a series of studies of vehicle climate a thermal manikin was used. The manikin is heated and temperature controlled in 33 independent segments, covering the whole body surface (Fig. 1).

The function and operation of a thermal manikin has been thoroughly described elsewhere (see e.g. (Holmér et al., 1992; Wyon 1989)). In brief, low-voltage power is pulsed to each segment at a rate, that allows the maintenance of a constant surface (skin) temperature, e.g. 34 °C. The power consumption under steady-state conditions is then a measure of the convective, radiative and conductive heat losses (dry heat loss). Measurements and regulation are taken care of by a computer system. The system is compact and can be operated in the field

Fig. 1 Example of a multi-segmented thermal manikin (Aiman2). Seat and thighs are modified to simulate compression during sitting. Segments are designed to maximise asymmetric effects.

from a battery and a DC-converter.

Typically, the quantity measured for each segment is the power consumption or heat loss, Q (in W/m^2). The following equations apply:

$$Q_{meas} = h_c \cdot (T_s - T_a) + h_r \cdot (T_s - T_r) + h_k \cdot (T_s - T_k)$$

where h_c , h_r and h_k is the heat transfer coefficients by convection, radiation and conduction, respectively. T_s is the manikin skin temperature (normally kept constant at $34.0^\circ C$), T_a is the air temperature, T_r is the mean radiant temperature of the environment and T_k is the surface temperature of the contact zone (e.g. the seat). It is clear from this equation, that segment heat loss is influenced by a number of factors. The direct measurement of Q eliminates the need for determining the other components. In contrast, measurements are required of all factors in the right part of the equation to get one value for the heat loss. Presently, no methods are available for this latter purpose, although mathematical models have become available for simulation purposes (Thellier et al., 1994).

Manikin heat loss and thermal sensation

In a first series of experiments total and local heat

Thermal Vote	Interpretation
+3	much too hot
+2	too hot
+1	hot but comfortable
0	neutral
-1	cold but comfortable
-2	too cold
-3	much too cold

Fig. 2 Scale for rating of thermal sensation and calculation of MTV.

fluxes were determined for a variety of climatic conditions (heat, cold, solar radiation etc.) and compared with thermal sensation votes and physiological responses of subjects exposed to the same conditions (Bohm et al., 1990). Thermal sensation was rated using the scale in Fig. 2. The individual votes were averaged for each condition and reported as a Mean Thermal Vote (MTV). MTV for all conditions was subjected to a regression analysis.

High correlation was found for segment heat flux and mean thermal vote (MTV) of subjects for the same body segments. For 29 out of 34 regressions the coefficient was higher than 0.8. 13 regressions were higher than 0.9. The lowest value was 0.64 for the right thigh during winter conditions. Results for whole body thermal sensation for 9 winter and 11 summer conditions are given in Fig. 3.

On the top x-axis in Fig. 3 the heat loss is given in W/m^2 . This is the measured manikin/segment heat loss. However, for the practical interpretation this value has little meaning for the practitioner, since reference val-

Fig. 3 Regression of Mean Thermal Vote on manikin heat loss and calculated Equivalent Homogenous Temperature for the whole body during winter and summer conditions. Regression correlation coefficients were 0.91 and 0.92 respectively. (modified from (Holmér et al., 1992)).

Fig. 4 Principle for calculation of acceptable temperature range or "comfort" interval. On the basis of the individual segment regression lines the temperatures corresponding to a MTV of -0.8 and $+0.8$ are graphically determined.

ues are not readily available. Wyon et al. (1989) suggested the use of a temperature concept, i.e., the temperature of a homogenous room in which the same amount of heat is lost, as in the actual conditions. This Equivalent Homogenous Temperature (EHT) should be easier interpreted and compared with everyday living conditions. By calibrating the manikin under homogenous, wind still conditions, all heat fluxes can be converted (and normalized) to an equivalent homogenous temperature (EHT). Accordingly, regression of MTV-values was performed with EHT-values. The regression equation allows the prediction of MTV on the basis of a value for EHT. In other words, a $MTV=0$ (thermal neutrality) can be accurately predicted. However, this is of little interest, since individual variation and design limitations will seldom allow a perfect climate.

Rather, a temperature interval corresponding to a defined variation in MTV around 0 of ± 0.8 would be the target for acceptable conditions. The value of 0.8 is arbitrarily chosen and may be set at lower levels depending on purpose. The principle for derivation of the temperature interval based on $MTV=0 \pm 0.8$ is illustrated in Fig. 4.

The procedure was repeated for the 18 different body segments for which subject votes were obtained (and for whole body). The sets of a low and a high temperature are plotted in a graph (see Figures 5-7). Hence, a "comfort" profile for the climate over the whole body surface is obtained (Bohm et al., 1990). The comfort profile is different for summer and winter conditions, mainly because warmer clothing is used under winter conditions.

Evaluation of cabin climate

A procedure was adopted for using the thermal manikin, to evaluate the thermal environment in vehicle compartments. The manikin is placed in the driver's (or passenger's) seat and the vehicle (or cabin) is placed in a climatic chamber.

Environmental conditions are defined and the manikin is heated and allowed to attain steady-state values of heat loss. This takes about 60 min from a cold start-up and about 15 min for a change of conditions when manikin is warm.

Heat loss values are converted to their corresponding EHT-values and plotted in the appropriate "comfort" profile (summer or winter). Truck cabins have been evaluated with their standard HVAC-systems for a variety of environmental conditions (Bohm et al., 1991). One example of the results is given in Fig. 5. It illustrates a difficult climatic problem - warm climate and sunshine. The results indicate that the resulting climate over the body surface is very heterogeneous. This is a combined effect of the solar radiation and the cold air from the air conditioning system. In order to maintain an acceptable whole body heat balance, large amounts of cold air has to be blown into the compartment.

The way this is done is critical to local heat balance. When cold air hits for example the left hand, it "feels" cold, whereas the right hand is heated by the solar radiation and "feels" warm. Also illustrated in the graph is the build up of a vertical asymmetry, cold air stays around the lower leg. The effect of the sun is most pronounced at the chest and thighs. It is also clear from Fig. 5, that the heat loss from the lumbar back and chest is small, resulting in high EHT-values. This is not sur-

Fig. 5 Test of an air-conditioning system of a truck cabin. Broken line shows the temperature profile obtained at an ambient air temperature of 30°C and sunshine from the front. (modified from (Bohm et al., 1991)).

Fig. 6 Temperature profile of a car seat used with (solid line) and without (broken line) seat ventilation. It is readily seen that most body parts shift to a higher temperature as a consequence of the increased heat loss of lumbar back and buttocks.

prising, as the seat is well insulated and little effected by the cold air. This problem is further discussed in the next section.

The possibility for spatial resolution of thermal influences (e.g. by solar radiation or convection currents) appeared to be very useful in the analysis of system performance.

Ventilated seats

The comfort profiles (see Figure 5 and 7) have been further validated and verified in subject trials with different car seats (Bohm et al., 1992). Ventilation of the driver's seat is a technical solution to reducing the normally high insulation of thigh, seat and back areas of the body. In fact, an effective ventilation should, at least in theory, make the seat transparent to the subject, i.e., increasing heat losses to the same or even higher levels

as if the subject sat in the air (!) Constructions, however, may vary in efficiency. In one system seat ventilation allowed for almost 1.5-1.9°C higher ambient conditions for unchanged general thermal sensation, in addition to the pronounced local effect (Fig. 6). In other words, the extra heat taken away with seat ventilation, could be compensated for by reduced heat loss from other body parts (by increasing air temperature), maintaining an unchanged whole body heat balance.

Whilst the increased heat loss with seat ventilation was clearly verified with the manikin, the associated subject thermal sensation changed relatively little. One reason could be that the actual body parts are in contact with the seat and under pressure. The sensitivity appears to be different for these zones. The "comfort" interval of 23-29 °C for lumbar back and buttocks is rather arbitrarily chosen and the subject of seat climate requires further investigation.

In experiments with wetted clothing, in order to simulate sweating, the cooling effect of the ventilated seat increased considerably. This was due to additional evaporative heat loss as well as a reduced insulation of the wet clothing.

Evaluation of design and construction components

In a recent study the effects of various technical measures related to cabin design and HVAC-system components have been investigated (Bohm et al., 1994). A test cabin was built and placed in the climatic chamber. The cabin was equipped with a modern HVAC-system from a truck manufacturer. The cabin allows various modifications to be easily made and subsequently tested.

The effect can be evaluated with the thermal manikin and the results are plotted in a profile chart (see Figures 5-7). The ideal result will be a mid-line drawn between the low and high border lines. In other words the best climate should provide

- a relatively uniform and optimal local heat loss all

Fig. 7 Effect of air inlet through perforated ceiling during winter (left) and summer conditions (right).

over the body surface,

- an optimal whole body heat loss.

Due to the complex interaction of cabin design and construction and the HVAC-system performance, it is often difficult to achieve both. The procedure for the tests were the following. A baseline for comparison was obtained with the best, possible setting of the standard HVAC-system. This result was plotted and compared with results after various modifications. An improvement should, theoretically and in practice, create a more optimal temperature profile than the standard condition, at the same whole body heat loss.

In the study quantitative data on the effects of for example heated windows, heated floor, air outlet positions and solar screens have been obtained. Fig. 7 shows the results of blowing air into the compartment through a perforated ceiling. The broken line shows the baseline conditions. It is interesting to note that the quite modern HVAC-system with panel configuration creates a considerable vertical temperature asymmetry - warm at the lower and cold at the upper body with heating (winter) and the opposite with cooling (summer). In other words these are the best conditions with optimal whole body heat loss, that can be achieved with the standard setting. The other line shows the improvements achieved by letting air into the compartment through a perforated ceiling. The temperature profile in both winter and summer conditions becomes more even and homogenous, also with preserved whole body heat balance.

It is apparent from these and other results that the manikin method allows objective and cost-effective evaluation of parameters in the early design and development phase and forms a valuable tool for optimising system performance.

Dry heat loss and sweating

Presently, all manikins used for vehicle testing measure only dry heat loss. There are at least two reasons for this.

Firstly the difficulties in building, operating and maintaining a sweating manikin are considerable.

Secondly the ultimate goal for cabin design and HVAC-system performance is the creation of comfortable or close to comfortable climatic conditions. In sedentary comfort conditions people are not readily sweating and the evaporative heat loss is of minor importance for heat balance. So, albeit it is true that the present manikin technique cannot be extrapolated to extremes of heat or cold, it is of less importance since the conditions are unacceptable anyhow and should be improved towards comfort.

In its present form the manikin is more suitable for steady-state conditions. Rapid changes during transient

conditions is not readily measured in a relevant way. More research work and complimentary methods are therefore needed for such conditions.

In conclusion, the manikin technique offers a relevant, accurate and practical method for quick and conclusive evaluation of the thermal environment in vehicles. Efforts are made to co-ordinate and compare the experience and methods applied in different laboratories working with manikins. A concerted European research program has been proposed. The method is presently the subject of a standardisation work within ISO.

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Correspondence to: Ingvar Holmér, National Institute of Occupational Health, S-171 84 Solna, Sweden