NEW ENERG Y-EF FIC IENT BUILDING CON CEPT S AFF ECT ING HUMAN T HERMAL COMFORT AND SENSAT ION

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ABSTRACT

Energy-efficiency seems to be one key-driver for whole building and construction industry in the future. Therefore, new construction and building service concepts are obviously needed. Most likely better thermal insulation levels and at least partly new heating and cooling solutions will be adopted. To avoid unpleasant indoor environment outcomes in future buildings, a holistic approach focusing on occupant aspects is recommended. Since thermal issues seem to be dominant cause of indoor environment complaints also in the future, it is very important to really understand true nature of both complex physical and physiological phenomena, influencing human thermal sensation and comfort. This paper aims to evaluate magnitudes and typical variations – as well as importance and dominance – of different internal and external heat transfer mechanisms of the human body.

INTRODUCTION

Improving energy-efficiency in the future buildings will bring unavoidable changes in structural and building service system design practices. Most likely indoor surface temperature levels of better insulating envelope components will increase during heating periods. At the same time surface temperature levels of at least traditional heating devices tend to decrease due to heating demand reduction. Therefore, there is an obvious need to evaluate the future design and dimensioning criteria of structural and building service systems – especially from an occupant's point of view.

That the internal human body temperature should be maintained at around 37°C dictates that there is a heat balance between the body and its environment. That is, on average, heat transfer into the body and heat generation within the body must be balanced by heat outputs from the body. That is not to say that a steady-state occurs, since a steady-state involves unchanging temperatures and temperatures within the body and avenues of heat exchange will vary; the point is that for a constant temperature there will be a dynamic balance. (Parsons 2002)

If heat generation and inputs were greater than the outputs, the body temperature would rise and if heat outputs were greater the body temperature would fall. The heat balance equation for the human body can be represented in many forms. However, all equations have the same underlying concept and involve three types of terms: those for heat generation in the body, heat transfer, and heat storage. The metabolic rate of the body (M) provides energy to enable the body to do mechanical work (W) and the remainder is released as heat (i.e. $M – W$). Heat transfer can be by conduction (K), convection (C), radiation (R), and evaporation (E). When combined together all of the rates of heat production and loss provide a rate of heat storage (S). For the body to be in heat balance (i.e. constant temperature), the rate of heat storage is zero ($S = 0$). (Parsons 2002)

Several excellent studies are published in this field. However, a vast majority of these studies are focused either on internal of external heat transfer mechanisms of the human body. This study pays attention to both of these aspects aiming to clarify importance and dominance of individual thermal interaction mechanisms and to offer more solid basis for predicting relations between energy-efficient building concepts and human thermal sensation.

HUMAN RELATED HEAT TRANSFER MECHANISMS AND MODELS

The widely accepted **conceptual heat balance equation** for the human body is

$$M - W = E + R + C + K + S \,, \quad (1)$$

where $M – W$ is always positive. E, R, C and K are rates of heat loss from the body (i.e. positive value is heat loss, negative value is heat gain). For an analysis of heat exchange between the body and the environment, Fanger (1970) uses the heat balance equation

$$H - E_{dif} - E_{sw} - E_{res} - C_{res} = R + C, \quad (2)$$

where H is metabolic heat production [W m^{-2}], E_{dif} is heat loss by vapour diffusion through skin [Wm^{-2}], E_{sw} is heat loss by evaporation of sweat [W m^{-2}], E_{res}

is latent respiration heat loss [W m^{-2}], C_{res} is dry respiration heat loss [W m^{-2}], R [W m^{-2}] and C [W m^{-2}] are net radiation and convection heat loss from the body, respectively.

ASHRAE (1997) gives equation for **total evaporative heat loss from the skin**

$$E_{sk} = E_{dif} + E_{sw} = \frac{w\left(P_{sk,s} - P_a\right)}{\left[R_{e,cl} + \frac{1}{f_{cl} h_e}\right]}, \tag{3}$$

where w is skin wettedness (having values between 0.06 and 1.0) [-], $P_{sk,s}$ is water vapour pressure at skin (normally assumed to be that of saturated water vapour at skin temperature) [Pa], $R_{e,cl}$ is evaporative heat transfer resistance of the clothing layer [m^2 Pa W^{-1}], f_{cl} is clothing area factor (the surface of the clothed body divided by the area of the nude body), and h_e is evaporative heat transfer coefficient [W m^{-2} Pa^{-1}].

For **total respiratory heat loss** ASHRAE (1997) gives the equation

$$C_{res} + E_{res} = [0.0014\, M\, (34 - t_a) + 0.0173\, M\, (5.87 - P_a)], \tag{4}$$

where t_a is indoor air temperature [°C], and P_a is vapour pressure at air temperature [kPa].

Dry **convective heat transfer** to and from the human body is most commonly calculated using equation

$$C = f_{cl}\, h_c\, (t_s - t_a)\,, \tag{5}$$

where h_c [Wm^{-2} K^{-1}] is convective heat transfer coefficient, and t_s [°C] is either skin or clothing surface temperature exposed to room air. This convective heat transfer from skin or clothing results from an airstream perturbing the insulating boundary layer of air clinging to the surface of the body. Generally, the faster the flow of air around the body, the thinner the boundary layer of air on the body's surface, and hence the lower the thermal insulation afforded the subject. The process of convection from a heated surface such as human skin or clothing can be further classified into three distinct modes: natural convection, where the air movement is driven purely by thermally induced buoyancy and generally confined to low ambient air speeds; forced convection at speeds generally higher than 1.5 m/s, and a region of mixed-mode convection prevailing at air speeds between these two limits. Table 1 shows the human body part heat transfer coefficient values, for both natural and forced convection conditions, defined by a set of laboratory measurements by de Dear et al. (1997). For the forced convective heat transfer coefficient they suggested a formula

$$h_{c\_forced} = B\, v^n, \tag{6}$$

where B is coefficient [W m^{-2} K^{-1}], v is ambient air speed [m s^{-1}], and n is a dimensionless exponent.
According to the well-known Stefan-Boltzmann law, each surface emits **thermal radiation** power per unit area as

$$E_i = \varepsilon_i \sigma T_i^{\,4}\,, \tag{7}$$

where E_i is thermal radiation power per unit of area [W m^{-2}], ε_i is emissivity of surface i [-], σ is the Stefan-Boltzmann constant 5.670 $\times 10^{-8}$ W m^{-2} K^{-4}, and T_i is surface temperature [K]. Total radiant energy leaving surface, called its *radiosity*, is the sum of the rates at which the surface emits energy and reflects or transmits it between itself and other surfaces. Imagine breaking up the surfaces of a room into a number (n) of discrete patches, each of which is assumed to be of finite size, emitting and reflecting heat uniformly over its entire area. If we consider each patch to be an opaque gray diffuse emitter and reflector, then, for surface i (Foley et al. 1994)

$$J_i = E_i + \rho_i \sum_{1 \le j \le n} J_j F_{j-i} \frac{A_j}{A_i}\,. \tag{8}$$

J_i and J_j are the radiosities [W m^{-2}] of patches i and j. E_i is the rate at which heat is emitted from patch i. ρ_i is the reflectivity of patch i [-]. $F_{j\text{-}i}$ is the view factor, which specifies the fraction of energy leaving the entirety of patch j that arrives at the entirety of patch i, taking into account the shape and relative orientation of both patches and the presence of any obstructing patches [-]. A_i and A_j are the areas of patches i and j [m^2]. A simple reciprocity relationship holds between view factors in diffuse environments (Siegel and Howell 1981):

$$A_i\, F_{i\text{-}j} = A_j\, F_{j\text{-}i}\,. \tag{9}$$

Thus, Eq. (8) can be simplified, yielding

$$J_i = E_i + \rho_i \sum_{1 \le j \le n} J_j F_{i-j} \tag{10}$$

Rearranging terms,

$$J_i - \rho_i \sum_{1 \le j \le n} J_j F_{i-j} = E_i \tag{11}$$

After solving these surface radiosities J_i simultaneously for each individual surface of a space, the net radiation exchange at a surface can be evaluated. The net rate at which radiation leaves surface i may also be expressed as:

$$-q_i = \frac{E_{bi} - J_i}{(1-\varepsilon_i)/\varepsilon_i A_i} . \qquad (12)$$

Equation 12 provides a convenient representation for the net radiative heat transfer rate from a surface, where (E_{bi} - J_i) represents the driving potential and (1 - ε_i)/$\varepsilon_i A_i$ represents the surface radiative resistance. Therefore, there is net radiation heat loss from the surface if the emissive power that the black surface would have, exceeds its radiosity. In the opposite case, the surface will be the net absorber. (Incropera and deWitt 1990, Tuomaala 2002)

Detailed human thermal modelling

At rest, approximately 56% of total metabolic heat production is produced by internal organs, about 18% in the muscles and skin, 10% in the brain and 16% within the other organs (Yildirim and Ozerdem 2008). Heat produced in the body should be absorbed by the bloodstream and convoyed to the body surface because of poor heat conductivity of the all body tissues. Therefore, the convective flow of blood throughout the body is very important in internal heat transfer. About 50-80% of the heat flow in the tissue is carried in or out of the tissue by the blood flow (Salloum 2007).

As core temperature of the human body rises above its neutral value, vasodilation occurs and cardial output increases dramatically. Nearly 100% of this increase goes to the skin tissue. For this development, a state of maximum vasodilation is achieved when core temperature reaches 37.2°C. At this state, the total skin blood flow rate may be as much as seven times its basal value. As mean skin temperature falls below its neutral value, vasoconstriction occurs. Skin blood flow, and therefore, cardiac output, decreases. At a state of maximum vasoconstriction, assumed to occur when mean skin temperature falls to 10.7°C, the total skin blood flow rate may be as low as one eight of its basal value (Smith 1991).

The transport of thermal energy by the blood flow in the micro-circular system, also called blood perfusion, is more important to heat transfer throughout the tissue than that in the macro-circulation. The blood-tissue interface area varies tremendously through the circulation system. For example, the approximate total cross section area of arteries in the body is 20 cm^2 while that of capillaries is 4500 cm^2. Therefore, the capillary forms the major site for exchange of mass and energy between the blood stream and surrounding tissue. The energy exchange between this micro circulation and tissue is further dependent upon the tissue and blood temperature distribution, the blood perfusion rate, and the thermo-physical properties of the tissue. Detailed description of the local distribution of blood perfusion to energy exchange is an intricate task. Thus, a modelling compromise is required in order to facilitate the analysis of the important effect of microcirculation on the tissue energy balance. An approach commonly employed for this compromise, which accounts the heat transfer behaviour between microvasculature and tissue collectively, is based on the application of energy conservation, which is stated as the amount of heat taken up by tissue (or control volume) per unit time is equal to the arterial temperature minus the venous temperature times the rate of perfusion (Fu 1995)

$$q_b = \rho_b \dot{V}_b c_{p,b} (T_a - T_v) , \qquad (13)$$

where q_b is heat transfer from perfusion blood flow to tissue [W], ρ_b is density on blood [kg m^{-3}], $\dot{V}_b$ volumetric blood flow rate [m^3 s^{-1}], $c_{p,b}$ is specific heat of blood [J kg^{-1} K^{-1}], T_a is the temperature of arterial blood coming into tissue [K], and T_v is the temperature of the venous blood flow leaving the tissue [K]. In many scientific papers people think it is reasonable to assume an almost complete thermal equilibrium between the exiting bloodstream and the surrounding tissue because of the condition of very slow blood flow in the capillary bed. (Fu 1995)

RESULTS AND DISCUSSIONS

Human body related heat transfer mechanisms, presented above, have different sets of input parameters and boundary conditions. Figure 1 presents evaporative and convection respiratory heat losses depending on indoor air temperature estimated by Eq. 4. (Metabolic rate is 100 W m^{-2}, total skin area 1.87 m^2, and relative air humidity 50%.)

Figure 2 presents values for evaporative heat losses from skin through moisture diffusion and sweating (E_{sk} = E_{dif}+ E_{sw}). In the base case, human metabolic rate is 100 W m^{-2}, total skin area 1.87 m^2, and relative humidity 50%, skin wettedness is 0.06 (corresponding to value when only natural diffusion, and no sweating, occurs) ambient air temperature is 25°C, skin temperature is 35°C, evaporative heat transfer resistance of the clothing is 0.015 m^2 kPa W^{-1}, clothing area factor (the surface of the clothed body divided by the area of the nude body) is 1.186, and evaporative heat transfer coefficient is 59.61W m^{-2} kPa^{-1}. In each separate sensitivity case, the base case input parameter values are varied and corresponding heat loss values are presented. In general, Eq. 3 gives values between 10 and 20 W for evaporative heat loss from skin through moisture diffusion under normal indoor environment conditions. The only exception for these values is evaporative heat loss for sweating (on right and bottom line of Figure 2). Namely, this sweating heat transfer phenomena is clearly the most dominant one having almost 300 W heat transfer potential for completely wet skin with wettedness index value of a unity.

Figure 3 shows potential heat power levels of blood perfusion in different body part skin tissues (in Watts per temperature difference between arterial blood coming to and the venous blood flow leaving the tissue, see Eq. 13). According to these results, it is obvious that skin tissue blood flow, and related thermal behaviour, in head and torso areas are the most dominant ones. For example in basal blood flow case these two body parts together are responsible for one half of total blood heat convection capacity. However, for maximum dilate condition the torso's role is clearly the most dominant with blood related thermal convection capacity of 65 W/K.

Figure 4 shows heat power levels of total blood perfusion in different body parts, where all tissue layers are included. Here the dominance of head and torso is even more obvious. In basal blood flow case, the head has proportion of 19% and the torso has proportion of 68% of the heat transfer potential of blood circulation. According to these heat transfer estimations for basal, minimum, and maximum blood perfusion rates in different body parts, there certainly is quite a huge heat transfer potential for skin tissues only. As an extreme, if all tissue layers of the torso has 2 K higher or lower temperature level compared to entering blood, there is a potential of almost 600 W heat transfer between blood and the tissue layers in maximum blood flow conditions.

Figure 5 shows dimensions and other boundary conditions when estimating convection and radiation heat transfer between an occupant and its environment. This test case is modified from quite widely used RADTEST case, which has been used for building simulation tool validation.

Table 2 shows heat transfer interaction between a human body and the test environment. Convective heat loss is evaluated by assuming uniform skin temperature of 33.7°C and a constant indoor air temperature of 22°C. All body part convective heat transfer coefficients are adopted from Table 1 for standing person in natural convection environment. Thermal radiation is simulated by assuming constant skin and space surface temperature values of a RADTEST simulation case. The results indicate dominance of radiation heat transfer when adopting the boundary values presented above. The results also show rather significant differences between various body parts even in this test case of a nude human. If a more realistic clothed human was simulated, obvious surface temperature deviations would have occurred, especially with partly clothed and partly bare skin sections. Such deviations would have caused even more net heat transfer variations between different body parts. Therefore, it is highly important to fully understand local net heat transfer between body parts and a surrounding environment.

CONCLUSIONS

Improving energy-efficiency of buildings will evidently require better thermal insulation in the future buildings. This, in turn, will change typical indoor surface temperatures of envelopes, and then indirectly traditional operative temperature levels of building service systems (radiators, convectors, thermally active building structures, etc). At the same time, the results of a detailed human thermal modelling clearly indicate dominant heat transfer phenomena (both heat generation due to metabolism and heat transfer by blood perfusion) into torso region. This suggests to sub-dividing the human body into body parts and to conduct a more realistic simulation of human body thermal behaviour (both anatomy and physiology) to fully understand thermal interactions between the human body and it's environment.

This study indicates that there certainly are methods and possibilities available to evaluate thermal effects of alternative energy-efficient construction concepts on the human body. However, such professional design should be based on thorough understanding of thermal interaction both within the human body, and between the body and surrounding space. Otherwise, inadequate structural and building service system design will either reduce energy-efficiency of the future buildings or cause problems with thermal sensation and comfort.

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Table 1.
Natural ($v < 0.10$ m s^{-1}) and forced convection heat transfer coefficients (h_c) for the nude thermal manikin standing and seated. (deDear et al. 1997)

Body part	$h_{c\_natural}$ [Wm^{-2}K^{-1}]		h_{c_forced} [W m^{-2} K^{-1}]			
	Standing	Seated	Standing		Seated	
			B	*n*	*B*	*n*
Head	3.6	3.7	3.2	0.97	4.9	0.73
Chest	3.0	3.0	7.5	0.66	9.1	0.59
Back	2.9	2.6	7.7	0.63	8.9	0.63
Pelvis	3.4	2.8	8.8	0.59	8.2	0.65
Upper arm	2.9	3.4	10.0	0.62	11.4	0.64
Forearm	3.7	3.8	12.6	0.54	11.8	0.62
Hand	4.1	4.5	14.4	0.56	13.4	0.60
Thigh	4.1	3.7	10.1	0.52	8.9	0.60
Lower leg	4.1	4.0	12.9	0.50	13.2	0.57
Foot	5.1	4.2	12.0	0.50	12.9	0.54
Whole body	**3.4**	**3.3**	**10.4**	**0.56**	**10.1**	**0.61**

Table 2.
Net convection and radiation heat transfer between a human and the RADTEST environment.

Body part	Heat transfer between an occupant and her/his surrounding environment [W]		
	Convection heat transfer	Radiation heat transfer	Total heat transfer
Head	6.9	4.2	11.0
Chest	12.4	6.2	18.5
Back	11.2	5.4	16.7
Pelvis	25.5	13.9	39.4
Upper arm	5.9	2.8	8.7
Forearm	3.6	2.2	5.7
Hand	1.7	1.2	2.8
Thigh	10.4	7.1	17.5
Lower leg	5.8	4.2	10.0
Foot	1.4	1.6	3.0
Whole body	**104**	**64**	**168**

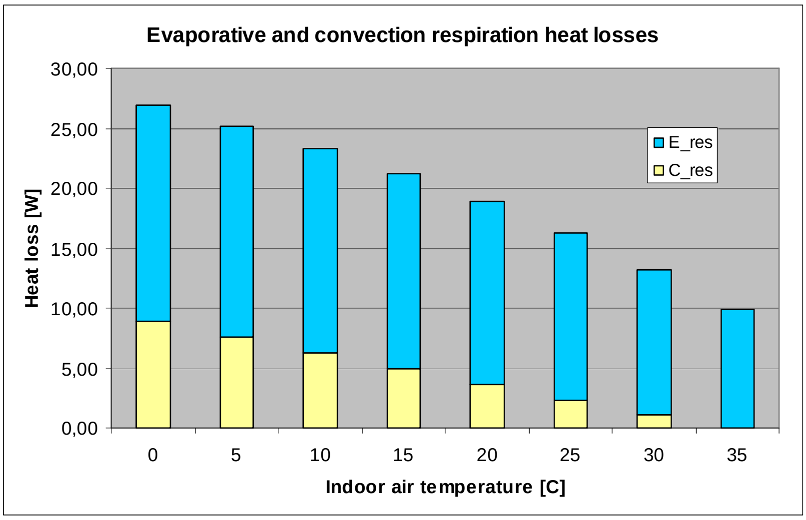


Figure 1. Human respiration heat losses depending on ambient air temperature.

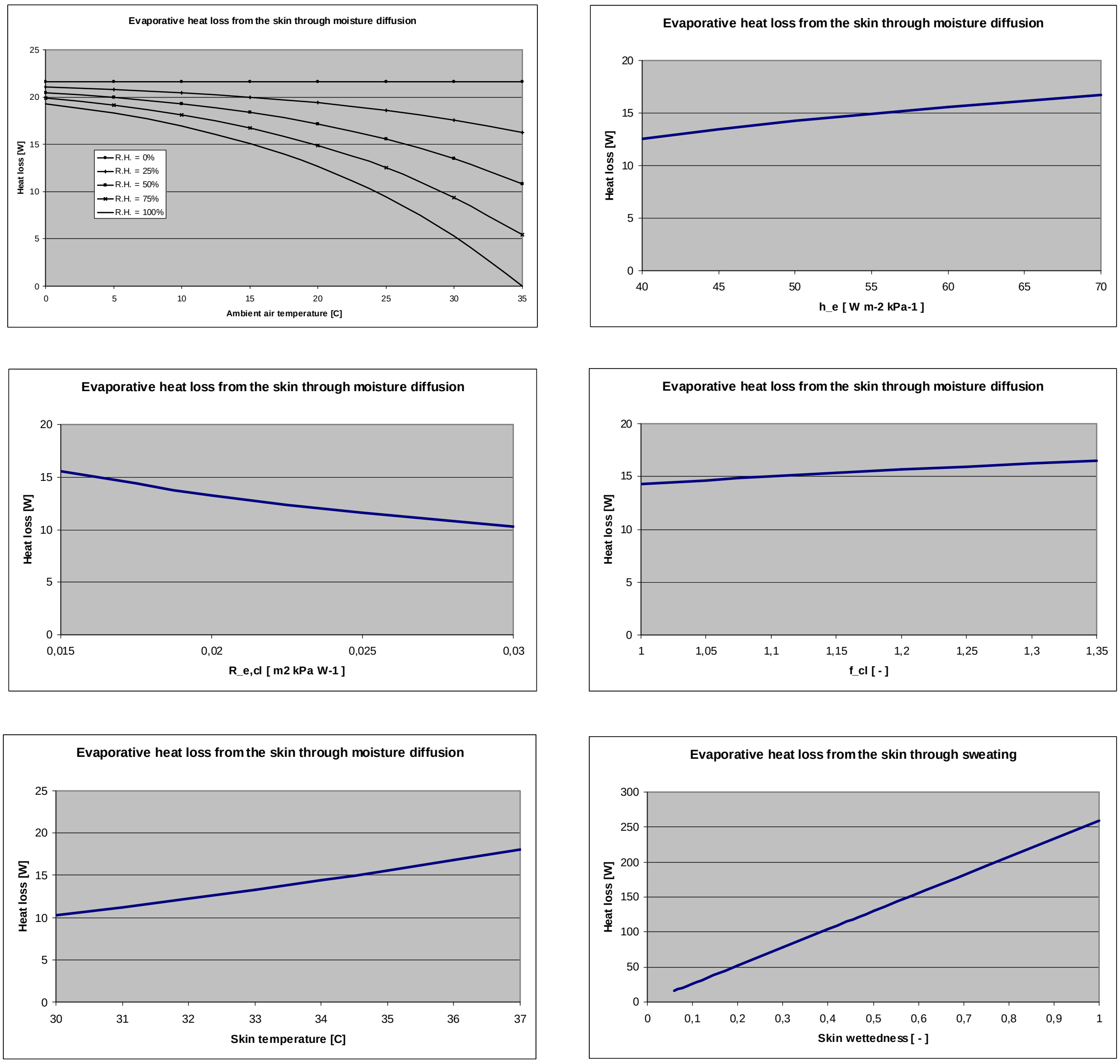


Figure 2. Evaporative heat losses from skin through moisture diffusion and sweating.

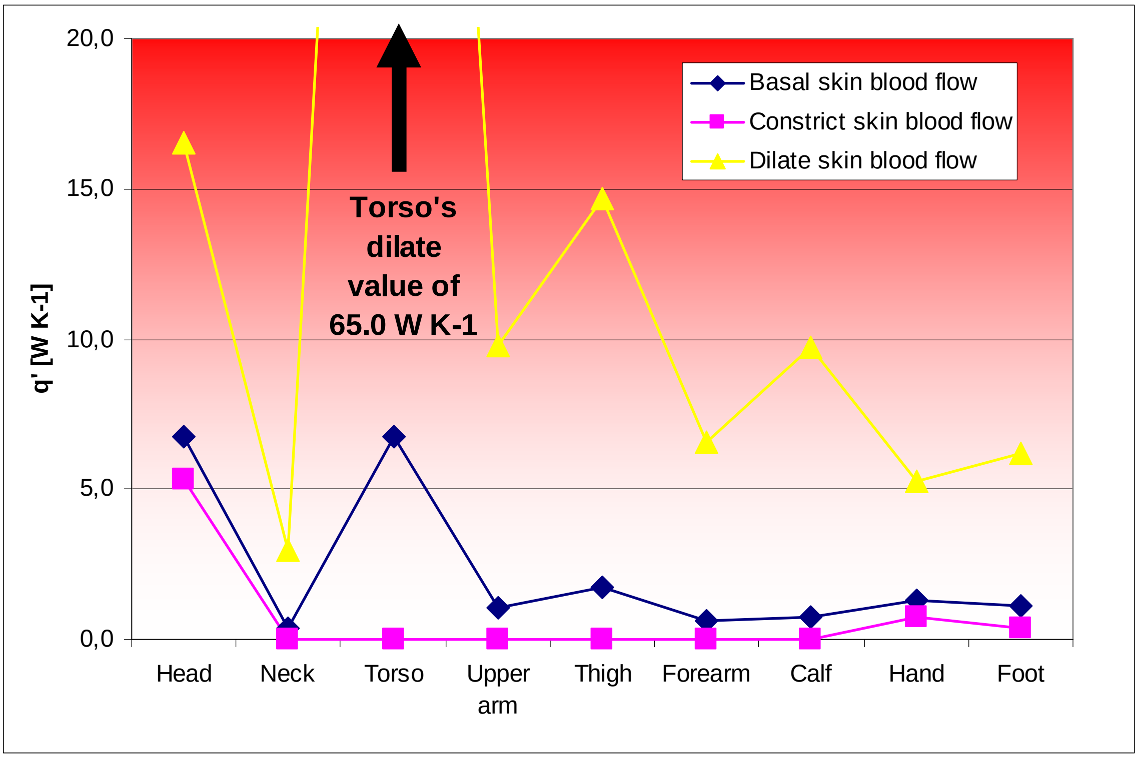


Figure 3. Specific heat power potentials of blood perfusion in skin tissues of different body parts (in Watts per difference between arterial blood and tissue temperature levels).

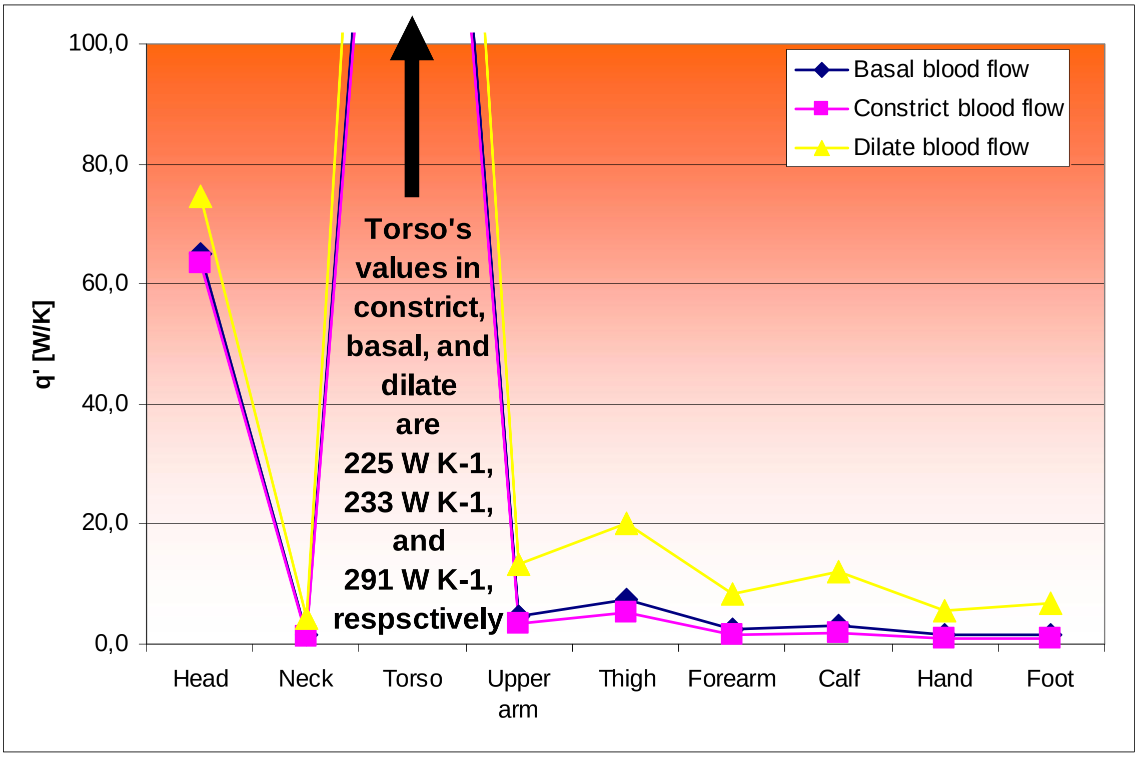
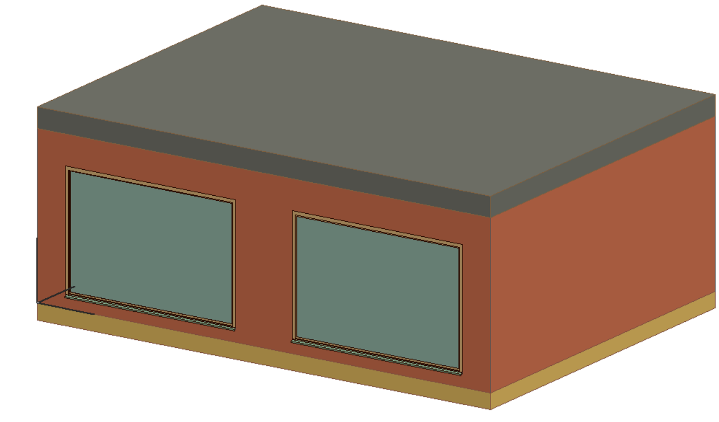


Figure 4. Specific heat power potentials of blood perfusion [W K^{-1}] in different body parts - all tissue layers included (in Watts per difference between arterial blood and tissue temperature levels).



Space dimensions

- floor surface 6 m x 8 m (48 m^2)
- room height 2.7 m
- two south-facing windows (2 x 6 m^2)

Temperature values

- air temperature 22°C
- indoor surface temperatures 22°C

Figure 5. Dimensions and the assumed constant surface temperature values the RADTEST environment.