Energy analysis of the thermal comfort

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ABSTRACT
A thermal comfort designer is especially concerned with creating an environment to improve the physical, mental and psychical health of human beings. The general thermal state of the body both in comfort and in heat or cold stress is dependent on an analysis of the heat balance for the human body. Traditional methods of thermal analysis are based on the first law of thermodynamics. By contrast, the second law of thermodynamics introduces the useful concept of exergy in the analysis. It enables the determination of the exergy consumption within the human body and the dependence on human and environmental factors. The results show that the lowest human body exergy consumption occurs at thermally neutral conditions; human body exergy consumption becomes higher in cold and hot environment. This approach also enables the exergetical analysis of heating and cooling system in connection with the thermal comfort, providing the lowest exergy consumption for both the systems.

INDEX TERMS
Comfort; HVAC system; Human response

INTRODUCTION

The complex interaction of air temperature, mean radiant temperature, air velocity and humidity makes up the human thermal environment. To achieve a satisfactory thermal environment, it is useful to be able to predict what the effect of a particular combination of thermal conditions will be on human occupants. The modern indoor design methods are based on the heat exchange conditions of the human body. The calculation of the heat exchange can be executed with the help of the so-called heat balance equation, as studies have proved that the subjective heat sensation is pleasant if the heat generated within the human body (metabolism) and the heat dissipated in the various ways are in balance. For comfort assessment of the indoor environment several methods are available (ISO 7730, 1995; ASHRAE 55, 1992). Typically, six parameters are used, requiring as input four indoor climatic parameters (ISO 7726, 1998) and two parameters related to the occupants: metabolic heat production (ISO 8996, 1989) and clothing insulation (ISO 9920, 1993).

For the optimal thermal comfort, three basic conditions must be satisfied. The first condition is the existence of a heat balance, based on the first law of thermodynamics, which is far from sufficient condition. Human thermoregulatory system is quite effective and creates heat balance within wide limits of the environmental variables. For a given activity level (metabolism), the skin temperature and sweat secretion are seen to be the only physiological variables influencing the heat balance. Consequently, the sensation of the thermal comfort has been related to the magnitude of these two variables. Experiments involving a group of subjects at different activity levels have been performed to determine mean values of skin temperature and sweat secretion as the second and the third basic conditions for thermal comfort.

The thermal comfort is a crucial issue for the proper assessment of the indoor quality of buildings. It should be considered both as a requisite by itself and as a fundamental preliminary requirement for establishing other indoors needs. Maintaining the declared values

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of factors determining thermal comfort constant, while eliminating any disturbing influences causing local thermal discomfort, ensures thermal comfort. On the other hand, considering heating, cooling and/or air conditioning, an engineer designing a system is expected to aim for the highest possible technical efficiency at a minimum cost under the prevailing technical, economic and legal conditions and also with regard to ethical, ecological and social consequences. Energy savings and emission reduction is both the matter of energy efficiency of the built environment and a matter of the quality of the energy carrier in relation to the required quality of the energy. Exergy analysis is a concept that makes this work a great deal easier. Tuning these qualities of energy is called exergy optimization (Bejan, 1988; Bejan *et al.*, 1996). The exergy concept has become an important tool for the analysis and the design of thermal systems that effectively use energy sources (Dincer, 2001). Therefore, it is important to have a clear image of the exergy balance of the human body in order to understand what the low exergy systems for heating and cooling of buildings are and how they acts on the human thermal comfort.

THERMAL COMFORT MODEL

The steady-state model developed by Fanger (1970) assumes that the body is in a thermal equilibrium with negligible heat storage. There is no shivering and vasoregulation is not considered because the core and skin are modelled as one compartment. The rate of heat generation equals the rate of heat loss and the energy balance can be written as:

$$M - W = Q_{\mathrm{c}} + Q_{\mathrm{r}} + Q_{\mathrm{e}} + Q_{\mathrm{c,res}} + Q_{\mathrm{e,res}} \tag{1}$$

where M is the rate of metabolic heat production, W the rate of mechanical work accomplished, Q_{c} the convective heat flow, Q_{r} the radiative heat flow, Q_{e} the latent heat transfer rate, $Q_{\mathrm{c,res}}$ the rate of convective heat loss from respiration and $Q_{\mathrm{e,res}}$ the rate of evaporative heat loss from respiration.

This simplified model does not attempt to simulate transients or thermal regulation and is focused primarily on the thermal physiology of the human body. However, a thermal model for the body is only as accurate as the information provided about the heat and moisture exchange with the environment. Consequently, if the indoor environment is controlled with HVAC system, the heat and moisture exchange with the environment must be evaluated since the thermoregulatory control mechanisms of the body are influenced by environmental conditions.

The effects of the ambient conditions on human thermoregulatory system and heat flow within the human body could be investigated with the two compartments (or two node) model developed by Gagge (1986). The model represents the body as two concentric cylinders, where the inner cylinder represents the body core and the outer cylinder represents the skin layer. The core and skin compartments exchange energy passively through direct contact and through the thermoregulatory controlled peripheral blood flow. A transient energy balance states that the rate of heat storage equals the net rate of heat gain minus the heat loss. This thermal model is described by two coupled heat balance equations for compartments:

$$S_{\mathrm{cr}} = M - W - (Q_{\mathrm{c,res}} - Q_{\mathrm{e,res}}) - Q_{\mathrm{cr}\to\mathrm{sk}} \tag{2}$$

$$S_{\mathrm{sk}} = Q_{\mathrm{cr}\to\mathrm{sk}} - \left(Q_{\mathrm{c}} + Q_{\mathrm{r}} + Q_{\mathrm{e}}\right) \tag{3}$$

where S_{cr} is the rate of heat storage in core compartment, S_{sk} the rate of heat storage in skin compartment and $S_{cr \to sk}$ the heat flow from core to skin compartment. The rate of heat storage in the body equals the rate of increase in internal energy. The rate of storage can be written separately for each compartment in terms of thermal capacity and time rate of change of temperature as:

$$S_{\mathrm{cr}} = (1-\alpha) \cdot m \cdot c_{\mathrm{b}} \cdot \frac{1}{A_{\mathrm{Du}}} \cdot \left(\frac{\mathrm{d}T_{\mathrm{cr}}}{\mathrm{d}t} \right) \tag{4}$$

$$S_{\mathrm{cr}} = \alpha \cdot m \cdot c_{\mathrm{b}} \cdot \frac{1}{A_{\mathrm{Du}}} \cdot \left(\frac{\mathrm{d}T_{\mathrm{sk}}}{\mathrm{d}t} \right) \tag{5}$$

where α is the fraction of body mass concentrated in skin compartment, m the body mass, c_b specific heat of the body and t the time. When the body is able to maintain thermal equilibrium with the environment at minimal regulatory effort, the state of physiological thermal neutrality is reached and the average core and skin temperatures: $T_{sk,neutral}$ = 33.7°C and $T_{cr,neutral}$ = 36.8°C. In the case of temperature deviations from these respective neutral set points, we could suppose the triggered thermoregulatory control process (vasomotorical, sweating, shivering). The core and skin temperature deviations act on blood flow, which is controllable. Since the heat is transferred from the core to skin passively (conduction by direct contact between compartments) and through the controllable skin blood flow, the combined heat flow is then:

$$Q_{\mathrm{cr}\to\mathrm{sk}} = (K + \dot{m}_{\mathrm{blood}} \cdot c_{\mathrm{blood}}) \cdot (T_{\mathrm{cr}} - T_{\mathrm{sk}}) \tag{6}$$

where K is the massless thermal conductivity (heat conduction from the core to the skin), $\dot{m}_{blood}$ the rate of blood flow between compartments and c_{blood} the specific heat of blood. The effect of blood flow changes the relative masses of the skin and core compartment. The activity of the sweat glands is set off by warm signals from the core and the skin. In the case of simultaneous cold signals from both the core and the skin, an additional metabolic heat through shivering and muscle tension is generated.

INTRODUCING THE EXERGY CONCEPT IN THERMAL COMFORT MODEL

The processes related to the human thermal comfort are heat and mass processes with one heat flow entering the skin compartment (‘heating device’) and two heat flows leaving it. One of the heat flows is leaving the human body due to the heat transmission, warming the exhaled air and due to the water diffusion and sweat evaporation. The other part of energy flow is leaving the skin compartment in the return blood flow going back to the body core (‘heat source’). Therefore, the input to such a system can be regarded as a difference between the heat input into the human body (metabolism) and the heat in the return blood flow. Splitting one heat flow into two will lead to irreversibilities and exergy losses. The exergy is thus transferred into the environment and controlled by the environmental conditions, influencing the heat and mass exchange. The general form of exergy balance equation, regardless of a system, is as follows:

$$\text{Input exergy} - \text{Exergy consumption} = \text{Stored exergy} + \text{Output exergy} \tag{7}$$

In the case of the human body, the exergy is generated by metabolic chemical reactions within the human body. One part of the input exergy is a portion of the sensible heat (with the availability to diffuse), while the other part is latent or wet exergy with the availability of evaporative dispersion of water into the environment.

The exergy entering the human body E_{in} can be described as:

$$E_{in} = \left(1 - \frac{T_{room}}{T_{cr}}\right) \cdot M + R_w \cdot T_{air} \cdot \ln(\varphi) \cdot \dot{m}_{evap} \tag{8}$$

where R_w is the gas constant for water vapour, φ the relative humidity of environment air and $\dot{m}_{evap}$ the evaporative mass transfer (diffusion, sweating and humidification of exhaled air). For the assumed environmental conditions (air temperature equal to mean radiant temperature, air velocity 0,1 m/s and relative humidity 50%) and physiological conditions (clothing insulation 1.0 clo and activity level 1.0 met or 58 W/m^2), the calculated exergy input for different models is shown in Figure 1.

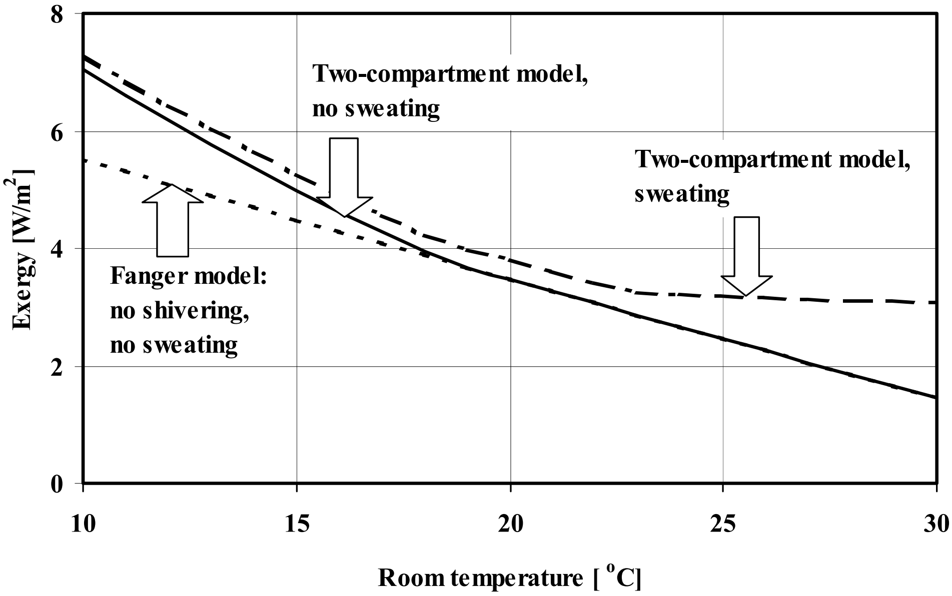

Figure 1 Dependence of exergy input for human body on room temperature.

Similarly, the human body exergy output can be calculated. The exergy output consists of dry and evaporative heat transfer (thermal exergy load) and of chemical exergy load caused with the water dispersion into the air (skin diffusion, air humidifying by breathing, sweating). In this calculation, the humidifying load is introduced into the room air at constant humidity ratio and constant air temperature and the calculated exergy output is shown in Figure 2.

Stored exergy is determined as the irreversibility due to finite heat transfer from the body core to the skin compartment and calculated as:

$$E_{stored} = \frac{T_{sk} - T_{cr}}{T_{sk} \cdot T_{cr}} \cdot T_{room} \cdot Q_{cr \to sk} \tag{9}$$

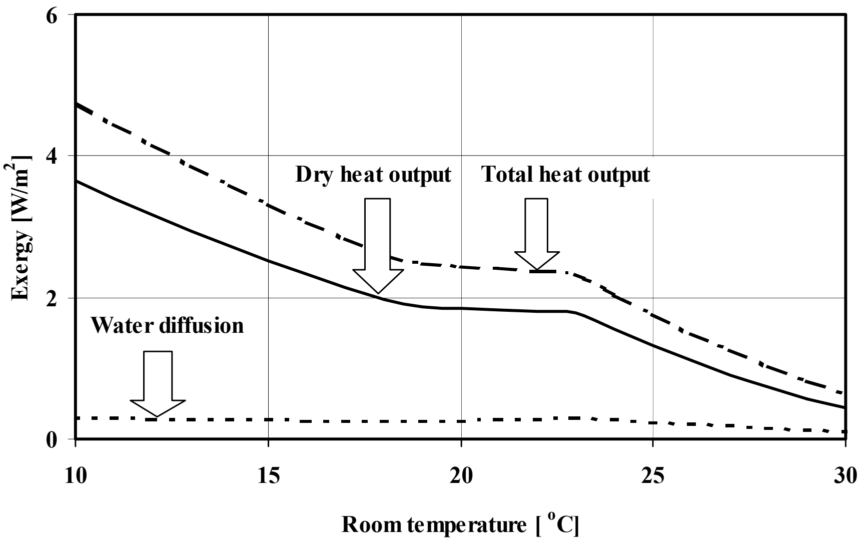

Figure 2 Dependence of the exergy output for the human body on room temperature.

The exergy consumption could be calculated with Eqn (7) and the result is shown in Figure 3. With the increasing room temperature from low to the neutral temperatures the exergy consumption rate decreases and at certain temperature reaches minimum (in our case 23°C). At low room temperatures the shivering generated energy (exergy) for maintaining the body temperature at (almost) desired level, caused higher exergy input and output. At lower skin temperature the stored exergy becomes higher as a consequence of temperature difference between core and skin. Similarly, when the environment becomes rather hot, the exergy consumption rate increases despite smaller temperature difference between the body and environment. In this case, sweating takes place, triggered by the temperature difference between the neutral and actual skin/core temperature. Evaporative cooling of the body increases the exergy consumption; such a process will allow the water to diffuse into the unsaturated air. According to Eqn (8), the driving mechanism is determined with the water vapour pressure and the saturated vapour pressure of the environmental air.

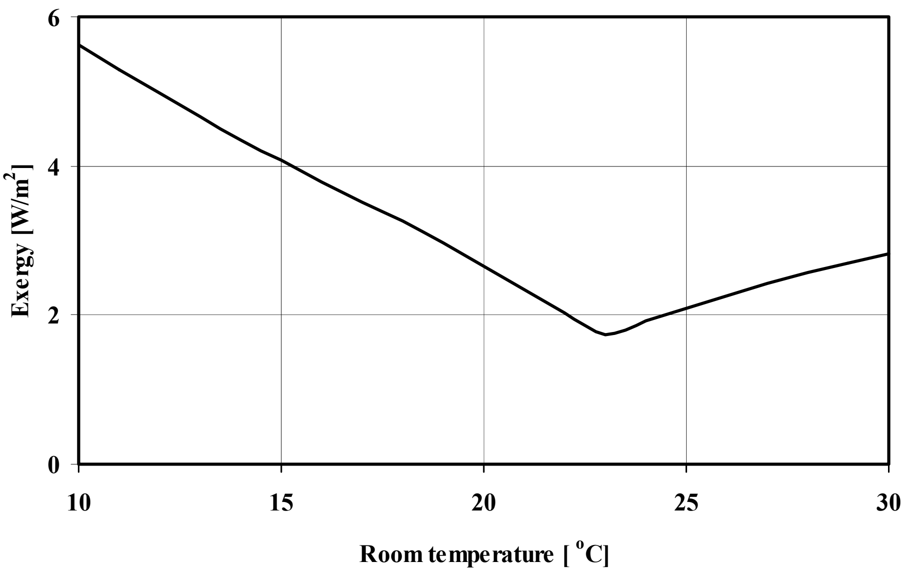

Figure 3 Exergy consumption within the human body as a function of room temperature.

CONCLUSIONS

A way to open up the saving potentials for room conditioning is given by the technology of extreme low temperature heating and cooling systems. These low exergy systems (using low valued energy) can provide room conditioning in a safe and economic way and at the same time, if it is properly designed, can improve thermal comfort. Introducing the term exergy in the energy research in building sector implies the exergetical analysis of the human physiological response to environmental conditions. This processes related to the human thermal comfort in connection with the temperature, heat and mass transfer. Therefore, in this analysis we used the Gagge two-node model, since it enables the implication of the second law of thermodynamics. It is shown that the existing methods for comfort assessment could be further expanded, taking into account the subjective heat sensation. With the model presented it is possible to investigate the effects of ambient conditions on thermal comfort, both based on the same thermodynamic law.

The aim of this analysis was to identify the exergetical model that would provide predictions of human responses to the thermal environment, based on exergetical analysis. Exergy analysis shows clearly how the human exergy consumption is coupled to environmental conditions. Furthermore, at a steady-state conditions, the results shows that there exists a correlation between exergy consumption of the human body and PMV value.

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