DYNAMIC THERMAL SENSATION IN PDEC BUILDINGS

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ABSTRACT In buildings with passive downdraught evaporative cooling (PDEC), occupants are subjected to environmental conditions which might be characterised by elevated relative humidities, increased air speeds, and time-varying internal conditions. A new physiological model which describes the human thermophysical system, and the active control exercised on it, has been produced. The model predicts skin and core temperatures, sweat rates, etc. on different parts of a seated, standing or exercising human. It also predicts the overall level of thermal discomfort for any set of time-varying, asymmetric environmental conditions, i.e. the dynamic thermal sensation, DTS. This paper illustrates the application of the model to the design of PDEC spaces.

1 Introduction

Passive Downdraught Evaporative Cooling (PDEC) is a means of ventilating and cooling buildings in hot, dry climates. The anatomy of a typical PDEC building comprises a ventilation tower open to the exterior air at its top and connected via openings to occupied spaces lower down. At the top of the tower a very fine mist of water particles is injected into the air using micronisers. These droplets evaporate in the warm, dry (ambient) air inside the tower raising its relative humidity (RH) and decreasing its dry bulb temperature (T_{db}). For example, during a typical southern European summer day at a state of T_{db}=35°C and RH=30%, it is possible to evaporate enough water to provide ventilation air at about a T_{db} of 27°C and an RH of 65%. This denser-than-ambient air then falls through the tower driving a ventilation flow of cool air through the occupied spaces (Robinson et al, 1999).

It is possible for small temperature depressions to induce high airflows. It is therefore likely that the micronisers will only be used to maintain a reservoir of cool air, which is then drawn off through variable sized openings into the occupied zones. During PDEC operation, the objective of the building management system is to provide air to the occupied spaces at an RH and T_{db} state that will provide thermal comfort.

2 Mathematical model of human thermoregulation and thermal comfort

In daily life people are exposed to a variety of thermal situations. Transient conditions, for instance, frequently occur due to time-varying environmental temperatures, air speeds, activity levels [met] and clothing levels [clo], etc. Exposures to thermally uncomfortable environments are associated with adjustments of the human thermoregulatory system and temporal changes in the bodily heat content can occur.

One reason for modelling the human thermal system was to extend comfort predictions to a wide range of different boundary conditions including arbitrary transients. Thereby, the model is based on the principle that any temporal change in a boundary condition (e.g. air temperature) will elicit the same change in comfort sensation as any other boundary condition (e.g. radiant temperature, or even arbitrary combinations of boundary conditions) which provoke the same dynamic change in the body's thermal state (Fiala, 1998).

The mathematical model of the thermoregulation consists of two interacting systems: the controlling active system; and the controlled passive system. The multi-segmental passive system model simulates the physical human body and the heat transfer phenomena occurring in it and at its surface. The active system predicts the regulatory responses of the central nervous system. The comfort model predicts the overall dynamic thermal sensation (DTS), and the associated percentage of dissatisfied people (Fanger, 1973).

2.1 Passive system

In the model, the human body is idealised as cylindrical and spherical elements: head, face, neck, shoulders, arms, hands, thorax, abdomen, legs, and feet - each comprising annular tissue layers of appropriate thermo-physical and -physiological properties: brain, lung, bone, muscle, viscera, fat, and two layers of skin with distinct physiological functions. Tissue layers were subdivided further into spatial sectors to allow for the treatment of lateral environmental asymmetries. The model represents an average person with respect to body weight (73.5 kg), body fat content (14%wt), Dubois-area (1.9 m²), basal metabolic rate (87 W), basal evaporation from the skin (18 W), and basal cardiac output (4.9 l/min).

Within the human body, metabolic heat is produced which is distributed over body regions by blood circulation and heat conduction from warmer to colder tissue locations. The dynamic heat transfer model considers also the effect of heat storage in living tissues. At the body surface, heat is exchanged by free and forced convection with ambient air, long and short wave radiation, and evaporation of moisture from the skin. Part of the bodily heat is lost by respiration. Local heat and mass balances were established for each individual body element sector to account for inhomogeneities with respect to environmental conditions, clothing insulation, and regulatory responses.

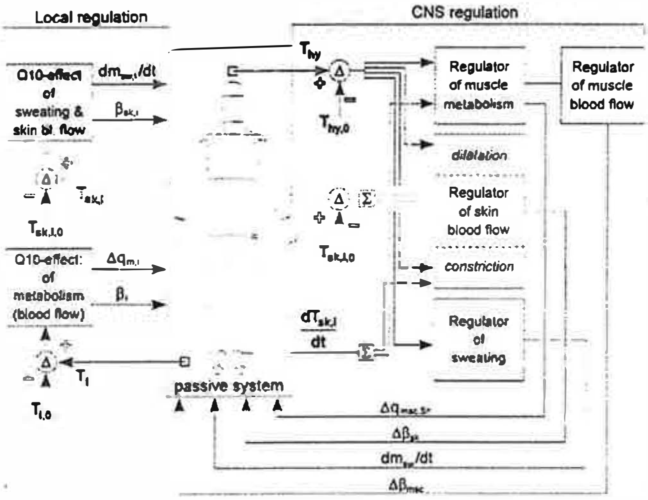

Fig. 1 Block diagram of the active system model. The central nervous system (CNS) thermoregulation accounts for overall changes in muscle metabolism $q_{msc,Sh}$ via shivering (and the corresponding changes in muscle blood flow, β_{msc}), skin blood flow β_{sk} via vasodilatation and vasoconstriction, and skin moisture extraction dm_{sw}/dt via sweating. The model uses temperatures of the skin (T_{sk}) and of the head core (hypothalamus, T_{hy}) as well as the rate of change of skin temperature ($dT_{sk,i}/dt$) as input signals into the regulatory centre. Local skin temperatures $T_{sk,i}$ are substracted (Δ) from the corresponding setpoint values $T_{sk,i,0}$ and form error signals $\Delta T_{sk,i}$. Positive difference represent 'warm' cutaneous recepetors, negative differences represent 'cold' thermoreceptors. The setpoint temperatures arise from the thermoneutral state of the (nude) body when reclining in an environment of 30°C where no thermoregulation occurs. The local afferent signals $\Delta T_{sk,i}$ are summed (Σ) to the integral signal from the skin ($\Delta T_{sk,m}$) which governs, together with ΔT_{hy}, the four responses of the CNS-regulation. The local autonomic regulation utilizes local skin and tissue temperatures, $T_{sk,i}$ and T_i, to modify local sweat rates, $dm_{sw,i}/dt$, skin blood flows, $\beta_{sk,i}$, tissue metabolic rates, $q_{m,i}$, and tissue blood flows, β_i.

2.2 Active system

Man maintains his internal temperature at a fairly constant value using four essential responses. Peripheral vasomotion, via suppression (vasoconstriction) and elevation (vasodilatation) of the skin blood flow, is activated to regulate internal temperature in moderate environments. In cold conditions, vasoconstriction is accompanied by shivering. In warm and hot conditions, vasodilatation is accompanied by sweating. A non-linear active system model has been developed by means of regression analysis using physiological data for steady state and transient exposures obtained from numerous published experiments (Fiala, 1998). A block diagram of the active system model is shown in Fig. 1.

2.3 Thermal comfort

Extensive comfort experiments covering a wide range of static and transient environmental temperatures, relative humidities, and activity levels were used to derive the following equation for the overall thermal sensation by means of regression analysis (Fiala, 1998):

$$DTS = 3\tanh\left[a_1 \Delta T_{sk,m} + g + \frac{0.11\left(\frac{dT_{sk,m}}{dt}\right)^- + 0.14\left(\frac{dT_{sk,m}}{dt}\right)^+_{max} \exp\left(-0.68\Delta t\right)}{1+g}\right]$$

$$g = 6.66\exp\left(\frac{-0.57}{\Delta T_{hy}}\right)\exp\left(\frac{-7.63}{5-\Delta T_{sk,m}}\right)$$

where: *DTS* is the *Dynamic Thermal Sensation* according to the 7-point-ASHRAE scale running from -3 to +3; a_1=0.30K^{-1} and 1.03K^{-1} for $\Delta T_{sk,m}$<0K and $\Delta T_{sk,m}$>0K, respectively; $\Delta T_{sk,m}$ and ΔT_{hy} are given in Fig. 1; $(dT_{sk,m}/dt)^-$ [K/h] is the negative rate of change of $T_{sk,m}$, $(dT_{sk,m}/dt)^+_{max}$ [K/h] is the peak positive rate of change of $T_{sk,m}$; and Δt [h] is the elapsed time since the occurrence of $(dT_{sk,m}/dt)^+_{max}$.

2.4 Model validation

Simulation results were compared and verified using measured data for about 300 different exposures obtained from independent physiological and comfort experiments (Fiala, 1998). The model was shown to reliably predict skin and body core temperatures, regulatory responses, and the overall thermal sensation for a range of environmental temperatures between 5 and 50°C, and exercise intensities between 0.8 and 10 met.

3 Evaluation of PDEC-controlled indoor climates

3.1 Predicted human responses to PDEC conditions

Human thermal, regulatory and perceptual responses were predicted for the range of temperatures expected to occur in PDEC buildings during the summer, i.e. temperatures T_{db} between 20 and 30°C for two RH levels of 30 and 80%. The simulation series was performed as individual two-hour-exposures to steady values of T_{db} in successive steps of 0.5K. When the PDEC system switches on, the mean radiant temperature T_r is likely to be close to T_{db} (Bowman et al, 1999). Therefore, in these simulations T_r was set to T_{db}. Furthermore, it was assumed that occupants were exposed to an air speed of 0.3 m/s and that there was no solar radiation, which is typical in the core of a PDEC building.

The analysis was performed for occupants engaged in typical office activities (activity level of *act*=1.2 met: ASHRAE, 1992) and wearing light summer clothing. This comprised briefs, socks, light long trousers, short sleeve shirt and street shoes which were applied to individual elements of the passive system. The summer dress was extended by modelling the chair which covers parts of the posterior leg segments. The *overall* resistance for this extended clothing ensemble was calculated by the model and resulted in a value of I_{cl}=0.55 clo.

Predicted components of the environmental heat exchange and the physiological and comfort reactions are plotted in Fig. 2. The dry heat loss of the human body, Qc+Qr, falls with increasing T_{db} from 130 W at 20°C to about 50 W at 30°C. In 'warm' conditions this reduction is accomplished by increased skin moisture generation (dmsk/dt) due to regulatory sweating which evaporates (Esk) keeping the resultant, total heat loss from the skin surface (Qsk) almost constant at about 110W over a temperature range of 26°C<T_{db}<30°C. The mean skin temperature (Tsk,m) varies in line with Qsk. The skin heat loss, and the dry and latent heat loss by respiration (Qrsp), is generally capable of balancing the heat gain by metabolism associated with the activity performed. As a result, the body core temperature (Tcore) is maintained within 0.2K over the whole range of T_{db}. In these thermal processes, changes in the skin blood flow (SBF), accompanied by the coupling effect of sweating in the warmth, are the governing thermoregulatory mechanisms. The dynamic thermal sensation (DTS) varies between 'cool' and 'warm', i.e. –2<DTS□+1.5. Thermal neutrality, (DTS→±0) appears to be associated with a narrow range of temperature between about 25°C<T_{db}<27°C for subjects at *act*=1.2 met exposed to va=0.3 m/s, and clad in summer clothing. The percentage of dissatisfied varies according to changes in the thermal sensation (Fanger, 1973).

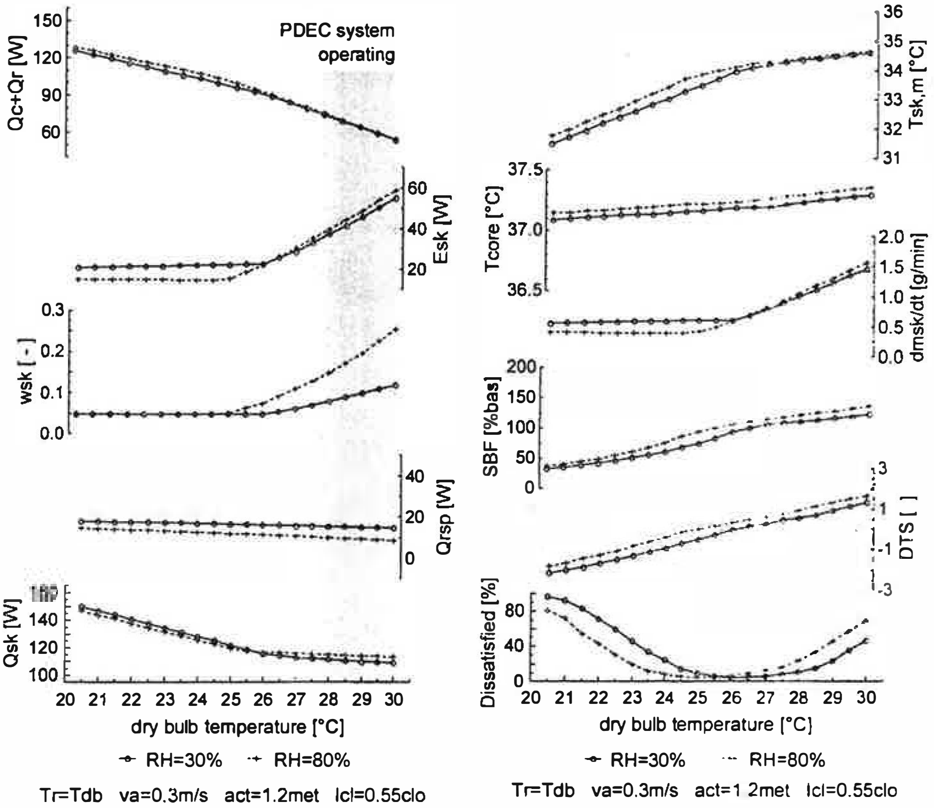

Fig. 2 Components of the environmental heat exchange (left) and physiological and comfort responses (right) predicted for occupants exposed to indoor climates of PDEC buildings

There is generally no pronounced effect of relative humidity, when RH≤80%, on human responses for these moderate dry bulb temperatures. Nevertheless, the wetted skin area ratio (wsk) (ASHRAE, 1993) rises more rapidly with T_{db} in the warmth when the evaporation of sweat is inhibited by the elevated water vapour pressure of air at high RH. It is apparent, however, that even RH's of 80% are acceptable for occupants within a range of about 24°C <T_{db}<28°C (the impact of RH within the comfort zone is described in more detail in the next section). Outside this range of environmental temperatures, a rise in RH from 30% to 80% causes an average increase in percentage of people dissatisfied of about 20%.

3.2 Comfort envelopes for PDEC-buildings

A series of simulations were carried out to establish zones of thermal comfort for PDEC buildings. In these buildings, ceiling fans might be used to enhance air movements, so air speeds from 0.3 to 0.8 m/s were studied. This assumes that occupants will accept increased air velocities in *warm* conditions without suffering from draught (see Fanger et al, 1988). This was shown experimentally for air speeds of up to 1.5 m/s (for references see e.g. Givoni,

1992) even though there was no subjective control of air speed. PDEC is a method of ventilating and cooling buildings in hot, dry climates. These climates are accompanied by increased solar radiation which influences the sensation of thermal comfort, so it was considered in the analysis.

In Fig. 3, comfort envelopes are plotted onto the psychrometric chart for air speeds of 0.3m/s and 0.8m/s. The impact of diffuse solar radiation at 25W/m² is also included. The remaining boundary conditions applied to the simulations are noted in section 3.1. Here, successive steps in RH of 5% between 10%<RH<90% were used. The assessment of comfort envelopes is based on a 10%-dissatisfaction-criterion (ASHRAE, 1992).

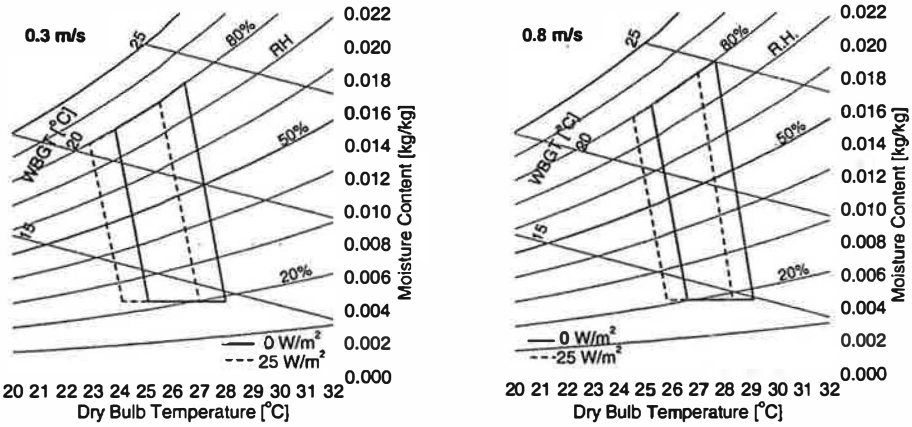

Fig. 3 Comfort envelopes for air velocities of 0.3m/s (left) and 0.8m/s (right). In both diagrams the shift of the comfort zone due to diffuse solar radiation of 25 W/m² is also indicated

The comfort zone was found to range between 24°C<T_{db}<27°C for va=0.3 m/s, and 25.5°C<T_{db}<28°C for va=0.8 m/s, both at RH=70% (which might be appropriate under PDEC operation). Diffuse solar radiation of only 25 W/m² was sufficient to cause a shift of these comfort envelopes toward lower dry bulb temperatures by 1K. The variation of RH with temperature was found to be linear at a rate of 2.5×10^{-2} K/RH% which agrees well with published data obtained from comprehensive experiments (Rohles et al, 1971).

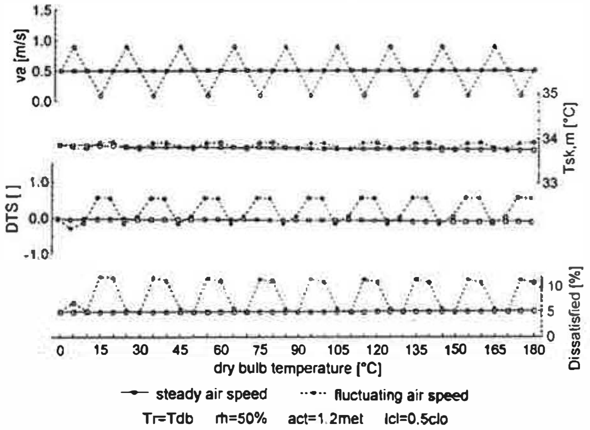

Fig. 4 Physiological and comfort responses to dry bulb temperature of 26°C predicted for steady and fluctuating air speed

The above results refer to exposures in which environmental parameters are held constant. However, in PDEC buildings environmental parameters may vary with time and affect the comfort of the occupants. This is demonstrated by a comparison of exposures to T_{db}=26°C with: (i) a constant air speed of va=0.5 m/s; and (ii) an air speed which fluctuates periodically around its average of 0.5 m/s by ±0.4 m/s at a rate of 9×10^{-2} m/s per min (Fig. 4).

In addition to local thermal discomfort which might be invoked (Fanger et al, 1988) fluctuating airflow appears to have an additional, specifically dynamic, effect on overall human thermal comfort which is associated with temporal changes of the mean skin temperature. Even though $T_{sk,m}$ is held within comfortable limits 33.8-34.0°C, positive and negative rates of change of the mean skin temperature ($dT_{sk,m}/dt$) caused by fluctuating air speed, elicit, as punitive signals into the human thermal system, discomfort and reduce the acceptability of environmental conditions as shown in Fig. 4.

4 Summary and concluding remarks

The method of low energy cooling of indoor spaces by PDEC generates indoor environments which are characterised by relative humidities of up to 80% at temperatures of about 27°C. Air velocities could be up to about 0.8 m/s, and close to windows there will be short wave solar gains. It is also anticipated that there will be temporal changes in the environmental parameters, in particular, air speeds.

A dynamic model of human thermoregulation and thermal comfort has been developed to predict physiological and comfort responses for a wide range of steady-states and arbitrary transients including conditions where adjustments of the human thermoregulatory system and dynamic changes in the bodily heat content occur. The model has been used to study responses of occupants exposed to PDEC controlled environments.

PDEC seems to produce moderate conditions whereby thermal stress reactions of occupants are avoided. There was also no profound effect of relative humidities up to 80% on the thermal state of the human body, comfort perception and thermal acceptability for temperatures (T_{db}) in the range of 24°C to 28°C. Outside this temperature range a rise in RH from 30 to 80% caused an average increase of people dissatisfied of about 20%.

Zones of comfort were assessed for PDEC buildings which extend the traditional comfort envelopes (ASHRAE, 1992) to environments with increased air velocities in which there is a moderate solar gain. Diffuse solar radiation of only 25 W/m² caused a shift of the comfort envelope toward lower dry bulb temperatures by about 1°C. Rapid changes in air speed were found to have a detrimental effect on the overall comfort perception and the associated percentage of dissatisfied building occupants. Thus, rapidly changing air speeds should be avoided.

5 References

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