COMFORT ANALYSIS AS A CRITERION FOR ENERGY MANAGEMENT

F. THELLIER, A. CORDIER, M. GALEOU, F. MONCHOUX , O. FUDYM
Laboratoire Energie Solaire Et Thermique de l'Habitat (LESETH)
UNIVERSITE PAUL SABATIER - 118, route de Narbonne
31062 Toulouse Cedex - FRANCE

ABSTRACT

Over the past decade many models have been developped to analyse thermal behaviour of buildings, but thermal comfort of occupants, which should never be forgotten, is seldom treated. The aim of this paper is to present three models created to get a complete tool to simulate thermal behaviour of a man in a real environment.

The simplest one is the "PMV-PPD", which calculates comfort indices. The two others are human thermoregulation model: "Gagge", a two-node model, which leads to several comfort indices, along with global thermal physiological variables and "MARCL" a 25-node model which calculates local variables.

These softwares have been improved by refining calculation of heat exchanges with environment, adding a better representation of clothings, and a postprocessor to translate physiological and physical data into thermal sensations. Controllers have been built up, using either indices or thermo-physiological variables, to regulate indoor thermal ambience.

Those models will be shortly described and their use will be discussed. Examples are given pointing out the usefullness of such models to find the best solutions to reach optimal environmental conditions for comfort of the inhabitant.

INTRODUCTION

Building simulation can be helpful for a better designing, to choose an improved heating or cooling strategy or to evaluate thermal and economical performances of a house. In each case, thermal comfort should remain in the mind of the engineer looking for a better conception. Unfortunately, most of the tools currently used are only capable of giving air temperature, which is far from being sufficient to characterize the actual thermal sensation of the inhabitant. Nevertheless, they are obviously useful, because most of the ambience control equipments are based upon the measure and control of physical parameters : air temperature, relative humidity, for example.

Air temperature measurement and its calculation through a model, is not very easy to do in the reality, but they become very simple, provided the thermometer is assumed to be at the right place and air fully mixed. In that case, there is no problem to fix a regulation temperature and to use it for control or to evaluate the thermal performance of the house.

A slight improvement comes from the use of Operative Temperature (T_{op}), including radiative temperatures and eventually velocity and relative humidity of air. This is a first attempt to take the occupant into account, through infrared exchanges and sweat evaporation possibility, still too simple to be satisfactory, but allowing an easy control of the ambience. Charts can be drawn giving the best combination of the physical parameters.

A new idea was to look at the effect of ambience on human body instead of the ambience itself, through models representing the thermal behaviour of human body.

Our contribution was the implementation in TRNSYS, a general software for house simulation (Klein 1971) of three new TRNSYS Types, of different levels of complexity, taking physiological reactions of the body into account : PMV, Gagge and MARCL.

To be ran successfully, these subroutines need some other TRNSYS Types which are not included in the original TRNSYS package. For example, an improved infra-red heat exchange processor, a clothing model or a subroutine leading to air temperature and velocity distribution. All these Types, and some others, have been written in our Laboratory. With our three physiological models, we can perform simulations including more sophisticated control techniques, based upon comfort indices, global (Gagge) and even local (MARCL) skin temperature and wettedness. An improvement is made with a post processor (TRIM) translating those data into thermal sensations. Control on these thermal sensations is now possible but not yet done (dashed and hachured parts on the diagram, Fig. 1).

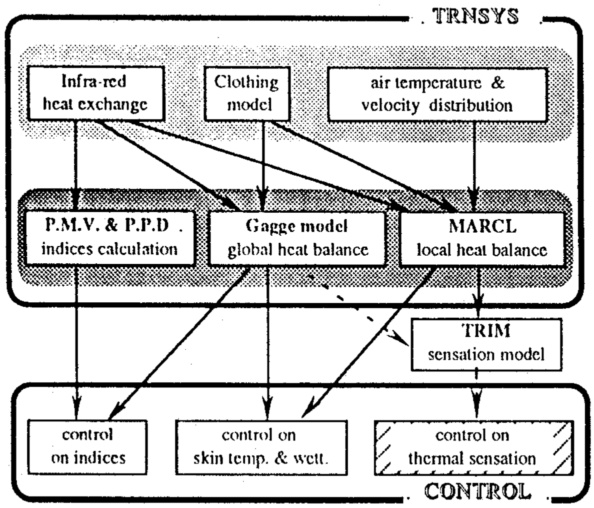

Fig. 1 : Thermal control possibilities and their required TRNSYS Types.

P.M.V. - P.P.D.

The first step was done by Fanger (1970) with the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). PMV is ground on thermal balance S of the body, between heat produced by metabolism (M—W, where M is the total metabolism, W the external work) and heat exchanged with environment through skin and respiration (E + R + C + Res, where E is sweat evaporation, R and C the radiative and convective transfers and Res, respiration includes latent and sensible heats). S is related to PMV, a vote scale, which is equal to zero for neutrality (S = 0), is positive or negative according to S sign, and varies from -3 (too cold) to +3 (too hot). PPD is deduced from PMV through a chart established after a great number of experiments.

PMV leads to a set of curves usefull to determine the values of the physical parameters giving and overall feeling of thermal comfort. It is generally used to characterize an inside ambience or to evaluate the thermal performance of a house, in terms of satisfaction of the occupant. Some attempts have been made to build up a PMV piloted control unit, maintening ambience within rècommanded values between +0.5 (slightly warm) and -0.5 (slightly cool). Those values correspond to PPD < 10% (less than 10 pourcent of dissatisfied person). This equipment does exist, but it seems to have been unsuccessful.

Simulation using a PMV based control is easy to do because the great simplicity of PMV Type ouputs, but not very helpfull because all ambience parameters are reduced to one index and the effects of each of them cannot be analysed separately.

Despite of the great improvement of PMV control versus usual technique, there are still too many simplifications for such a method to be sufficient. PMV is used to determine how far from equilibrium the body is, but formulae used to compute it are only valid for equilibrium. A more important drawback of PMV is that it only applies to steady state, in homogenous conditions. A similar result is given when all the body is at neutrality and when simultaneously feet are too hot and head too cold : PMV is helpless to determine the effect of heating floor on comfort, for example. The time constant of the body, with its physiological reactions, is about 1 or 2 hours. So, PMV must be used for longer periods only, but indoor climate seldom remains at a constant value during more than 2 hours.

HUMAN THERMOREGULATION MODEL

A better accuracy in the determination of physiological parameters is given by the use of models, including heat exchanges and physiological thermoregulation processes. The thermal network of the body is made up from a set of nodes, the number of which varying from 2 to about 250. Internal heat exchanges are due to thermal conduction between contiguous layers and to forced convection through blood flow. External heat exchanges include sensible (conduction, convection, radiation) and latent heat (sweat evaporation, respiration). Physiological reactions, in charge of the maintain of a constant internal temperature, are shivering and vaso-constriction, against cold environment, sweat emission and vasodilatation against hot climate. Those models can lead to the thermal sensation.

Gagge model : This model (1973) is composed with 2 nodes and admits a layer of clothes. It has been improved by addition of a more complex model of heat and mass transfer through clothing (Cordier, 1989), which takes into account transients states, vapor absorption and desorption in fibers, and moment induced ventilation through the fabric, between skin and clothes, called "pumping effect". It has been validated through experimental data and gives good results.

Fig. 2 shows an example of Gagge model results. Experimental procedure is as following (Vogt et al., 1983) : after half an hour of neutral period (at rest, T_{op} = 28°C), nude subjects start to pedal in a "cold convective" ambience (T_{air} = 21°C, T_{walls} = 31,2°C) during 75 minutes and then get dressed until the end. Experimental results (thick line) are compared with the Gagge model computed values, with (thin line) or without (dashed line) clothing ventilation (pumping effect). Additionnal clothing model gives obviously better results.

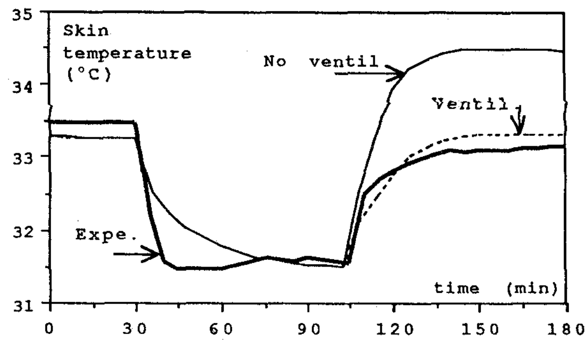

Fig. 2. Example of Gagge and clothing model results. Experimental mean skin temperature from experiment and from Gagge model with or without ventilation.

On account of its simplicity, Gagge model is rather currently used when we need a global response of the body placed in an homogeneous ambience, which can be variable with time. Its principal outputs are global physiological variables (skin temperature and wettedeness, evaporation rate, etc..), but also many indices (SET, PMV, WBGT, etc..). All those indices can be used in turn to control ambience.

MARCL : When local thermal sensations are needed, for example to determine if a heating floor can induce a bad sensation on feet level, the use of a more sophisticated model is required. Among all the possibilities, we choose the model written by Stolwijk and Hardy (1971) for NASA and improved its performances by a better account of external heat exchanges (Thellier, 1989a).

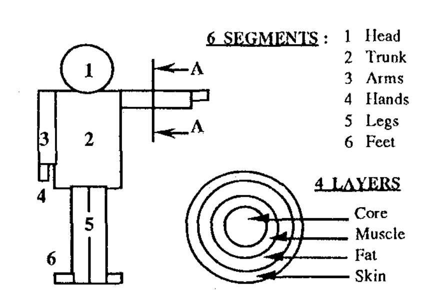

Fig. 3. Representation of the body in MARCL

In this model, renamed MARCL, body is divided into 6 parts (head, trunk, arms, hands, legs and feet), each of them being in turn divided into 4 layers (core, muscle, fat and skin). Blood, assuming a thermal link between all these compartments, is 25th node of this model representing the human body and its physiological thermoregulation, with a high enough complexity for our purpose.

This model accepts as inputs environmental data, variable with time, which can be different for each part of the body. Infra-red heat exchange, air velocity and temperature distribution Type computing are then needed. Outputs of MARCL are all the physiological parameters, such as local and mean skin temperatures or wettedness, the amount of sweat evaporated or not, the intensity of physiological reactions, etc. The great number of outputs is an important asset of this program, for it allows the choice of the right parameter, but it may also be a drawback, because it is always difficult to look simultaneously at a lot of parameters, if there is no synthetic variable or index to help conclusion. Such an index is wanting in MARCL.

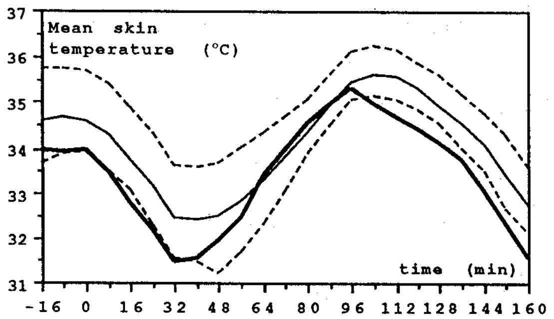

Fig. 4. Experimental (thin line) and calculated (thick line) mean skin temperatures versus time

MARCL has been validated by comparisons with experimental data. The results shown on Fig. 4 come from the following experiment (Grivel et al., 1989, Thellier, 1989b) : after a period of neutrality for subject nude and at rest (T_{op} = 28.8°C), air and wall temperature are modified by step of 2°C every 8 minutes, going down for half an hour from time zero, then up during one hour, and then down again, back to the beginning value, during one hour. Experimental and calculated mean skin temperatures are reported on this figure. Agreement was found rather good, even if MARCL computed temperatures (thick line) seemed to be slightly ahead experimental ones (thin line). Computed values usually lie within the inter-individual differences (dashed lines).

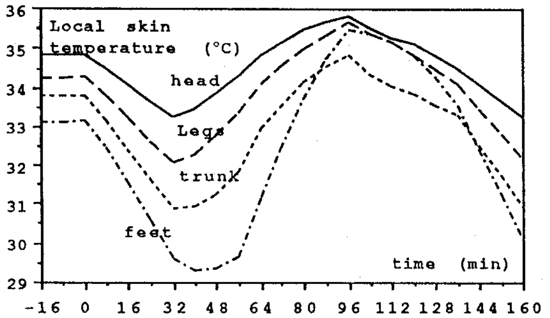

Fig.5. Local skin temperature variation for the same experiment as in Fig. 4

The interest of this model is to calculate local heat balances and temperatures. Fig. 5 gives four local skin temperatures (head, trunk, legs and feet) out of the 6 given by the model. Feet temperature exhibits wide variations ; they are more sensible to climatic changes, and therefore often causes local discomfort.

HUMAN MODEL UTILIZATION

Control on physiological parameters. The knowledge of physiological parameters can be usefull to control an ambience. We did a 24 hour simulation of a house, heated by a heating floor and an instantaneous auxiliary system, with a variable flowrate air renewing. Control is guided by skin wettedness (if greater than a limit : air flowrate is increased) ; mean skin temperature (heating floor is switched on if lower than a fixed value) and feet skin temperature (auxilary is switched on instead of heating floor if it goes beyond a limit). Results of this sophisticated regulation are compared with those obtained with a classical air temperature control. Fig. 6 and 7 show respectively floor and feet skin temperature variations with time in the two cases.

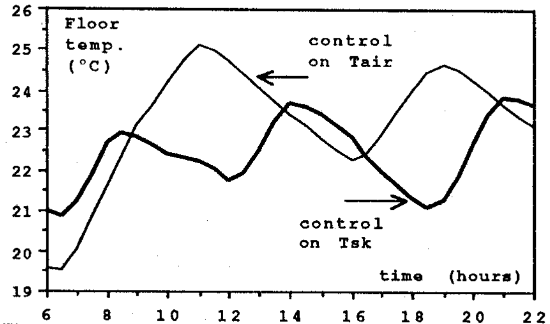

Fig. 6. Floor temperature for control on air temperature and on skin temperature.

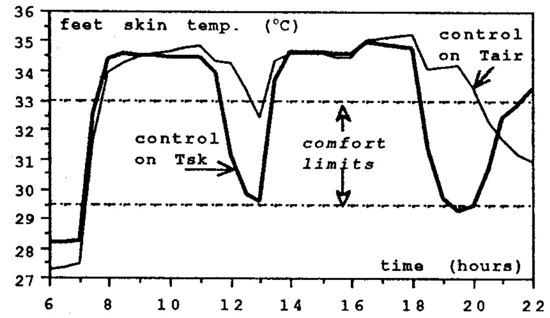

Fig.7. Feet temperature for control on air temperature and on mean skin temperature.

THERMAL SENSATION EVALUATION

Knowledge of skin temperature is very important but still insufficient : when arm skin temperature is 33.5°C, what is the thermal sensation of the occupant ? Answer is not as simple as it may appear at the first glance. It depends upon activity (metabolism) and clothes insulation, for example. A set of tables giving correspondances between sensation and local or global variables can be established, based upon a very wide review of experimental results reported in the litterature (Galeou et al., 1989).

We wrote a post-processor (TRIM) capable ... ting the physiological outputs of MARCL into ... sensations. It considers two possibilities for activity (lig... ...r heavy, the boundary being a metabolism of about 125 W) as well as for clothing (summer or winter clothes).

The validation of this program has been made with a set of experimental results, (which had not been used to make up the correspondance tables used in TRIM), giving thermal sensations expressed by subjects and the corresponding skin temperatures. Results are shown on Fig. 8. Experimental procedure has been previously described (Fig. 4 and 5) ; subjects were required to give their thermal sensation (S_{exp}). S_{cc} curve represents the thermal sensation computed from the skin temperature calculated by MARCL.

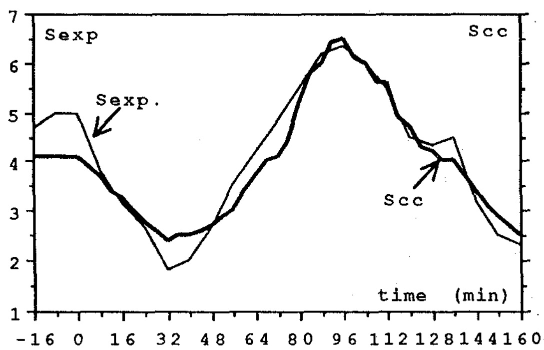

Fig. 8. Calculated and experimental thermal sensation for the same experiment as Fig.4 and 5
(Scale : 1-cold ; 2-cool ; 3-slightly cool ; 4-neutral ; 5-slightly warm ; 6-hot)

The next step will be to build up a control strategy grounded on thermal sensations, which are far more important for the occupant than skin temperature. Though, we plan to perform it in a near future, we are fully conscious that a lot of work has to be done to complete the study of a satisfactory comfort based on thermal control of houses.

REFERENCES

Cordier A., F. Monchoux, G. Serin and F.Thellier. 1989. "Influence du Vêtement sur le Confort Thermique : Modélisation en Régime Dynamique". In *Proceedings of JITH no 2*, 645-651 .

Fanger P.O.. 1970. "Thermal Comfort". *McGraw Hill*, New-York.

Gagge A.P. 1973. "Rational temperature indices of a man's thermal environment and their use with a 2-node model of his temperature regulation". *Fed. Proc. 32*, 1572-1582.

Galeou M., V. Candas and F.Grivel. 1989. "Le confort thermique : aspects physiologiques et psychosensoriels". Etude bibliographique. CNRS/INRS, LPPE Strasbourg, France (report).

Grivel F., A. Hoeft and V.Candas. 1989. "Body temperatures during warm and cool periodic transients : influence of clothing". Adv. in Indus. Ergo. and Safety, 1:

Klein S.A. and W.A. Beckman. 1971. "TRNSYS, a simulation program". *ASHRAE Trans.*, n°76.

Stolwijk J.A.J. and J.D. Hardy. 1971. "Control of body temperature". *Handbook of Physiology - Reaction to Environmental Agents*, 45-68.

Thellier F. 1989. "Modélisation du comportement thermique de l'homme et de son habitat. Une approche de l'étude du confort". *Thèse de l'Université Paul Sabatier no 510*, Toulouse, France.

Thellier F., A. Cordier, F. Monchoux, G. Serin, F. Grivel and V.Candas. 1989. "Influence de l'environnement sur le corps humain : Modélisation d'un bâtiment occupé". *Proceedings C.I.B.*, 1, 321-328.

Vogt J.J., J.P. Meyer, V. Candas, J.P. Libert and J.C. Sagot. 1983. "Pumping effects on thermal insulation of clothing worn by human subjects". *Ergonomics*, 26 (10), 963-974.