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MODEL-BASED METHOD TO MEASURE THERMAL COMFORT IN BUILDINGS

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Abstract: *This paper describes a practical method of measurement a HVAC control new variable. The method is based upon model-based estimation of thermal comfort. The thermal comfort is the only physical value, that truly corresponds to the changed (due to dynamic processing) environment conditions in buildings. The dynamic processing is a consequence of a modern demand-driven decentralized room climate control, that has been presented earlier, or a consequence of improvement of wall thermal insulation, that is beyond the limits of the actual insulation standards (for example 2002 - Energy saving regulations in Germany). The differences between various model types will be discussed. Some results will be shown for the realized model type.*

Keywords: Estimation method, Measurement method, Thermal comfort, Indoor climate control, HVAC

1. INTRODUCTION

In a number of publications some modern tasks and problems of energy saving in buildings have been discussed [1,2,3,4,5]. One of interesting ways to solve them is demand-driven decentralized room climate control. It helps not only to improve the heating strategy itself, but also to broke existing limitations for the approved in the industry process to improve thermal and air insulation in buildings. The limitations exist because of uncomfortable and sometimes dangerous situations for human health in insulated space (for example: high temperature oscillations, high air pollution, condensations and mildew hazards, etc.)

The realization of demand-driven decentralized room climate control particularly depends on acquisition techniques for related to the controlled state physical variables. In this article we shall discuss only problems of thermodynamic state as an important part of environmental control task.

It was found out that thermal comfort could be measured as function of many objective physical variables [6]. Then thermal comfort can be measured as PMV (predicted mean vote) (1) or PPD (predicted percentage of dissatisfied) values. The both variables are related to each other.

$$PMV = \left(0.352e^{-0.042(M/A_{Du})} + 0.032\right)\cdot\left[\frac{M}{A_{Du}}(1-\eta) - 0.35\left[43 - 0.061\frac{M}{A_{Du}}(1-\eta) - p_a\right] - \right. \quad (1)$$

$$\left. -0.42\left[\frac{M}{A_{Du}}(1-\eta) - 50\right] - 0.0023\frac{M}{A_{Du}}(44 - p_a) - 0.014\frac{M}{A_{Du}}(34 - t_a) - 3.4\cdot 10^{-8} f_{cl}\cdot\right.$$

$$\left.\cdot\left[(t_{cl}+273)^4 - (t_{mrt}+273)^4\right] + f_{cl}h_c(t_{cl} - t_a)\right]$$

where:

I_{cl} - Clothing thermal resistance, t_{cl} - clothing temperature, f_{cl} - clothed/naked surface ratio, t_a - air temperature, t_{mrt} - middle radiation temperature, A_{Du} - skin surface of human body, p_a - air pressure, h_c - convective heat transfer factor, η - mechanical work efficiency, M – metabolism.

The standard way to measure thermal comfort is to use complex devices like shown in Fig. 1. It consists of a number of sensors. Some of them measure geometry-related variables (for example radiation temperature) and should be placed immediately at the occupants position in the room. This means, that:

- a number of measurement devices are necessary for acquire thermal comfort for each of the present occupants,
- the measurement devices should be mobile in order to follow the occupants,
- the measurement devices should not be in the way of the occupants.

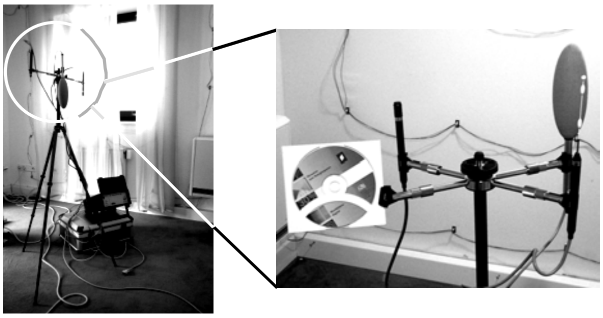

Fig. 1 – Data Logger for thermal comfort accordin to ISO 7730. Firma INOVA Type 1221C, UA1276 with MM0060, MM0038, MM0037 (left); Comparison of sensors size with a CD (right).

Considering the sizes of the measurement transducers (see Fig. 1) these conditions can not be realized. The direct acquisition of thermal comfort should be replaced by an indirect acquisition method.

2. MODEL-BASED METHOD

The thermal comfort model-based method of measuring in buildings is a part of complex HVAC system shown in Fig. 2. The hardware realization of the system has been mentioned in earlier works [2, 3, 7].

The main idea is to use a complex thermodynamic model to obtain the PMV-variables at any occupant's position. The model becomes values related to the actual thermal state as a number of physical values, which are measured outside of the living zone. (The living zone is normally defined as volume in a room, that is distanced 0,5 m from the walls and is 2 m high from the room's floor.) I.e. the model estimate thermal comfort due to calculation with a priori data and easy measured physical values, which do not contradict with the measurement criteria above (see Fig. 3).

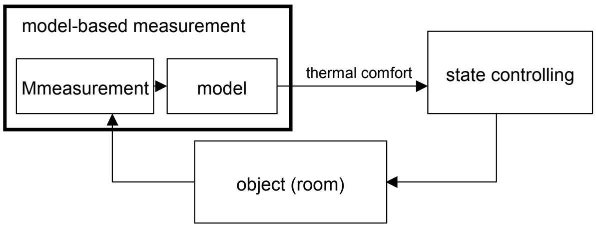

Fig. 2 – Scheme. Model-based technical system to preserve healthy living conditions in buildings.

The thermodynamic model can be developed using three main techniques [8]:

- experimental modeling,
- theoretical modeling,
- expert modeling.

In industrial applications the experimental modeling technique cannot be efficiently used because of large system times. Generally system time is about N*10 hours and a wide variety of weather conditions prolong the tuning phase of normal buildings up to several weeks. It would be too expansive in a real building industrial process.

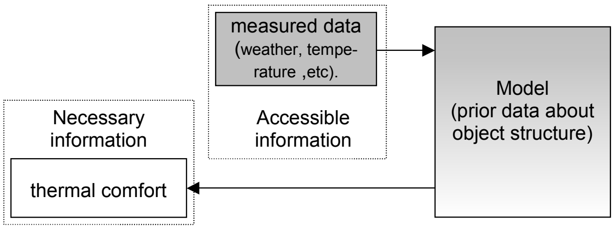

Fig. 3 – Principal measurement techniques to obtain thermal comfort in the living zone.

The expert modeling technique provokes high probability of imprecise control parameter. Besides, many high-qualified experts will be necessary for this modeling method in the building industry. This is a practically impossible requirement for the next few years.

Theoretical modeling can be used to solve the problem. On the other side it requires approved complex of thermodynamic models, which describe all important physical phenomena in the controlled room. This method replaces the human resource (what is necessary in expert and experimental modeling) through the capital investment.

The investment consists of two components: a very expensive modeling at the development stage and a computing hardware at the using stage. It is significant that the high development costs become to be irrelevant for the end product because of economy of scale.

3. THERMODYNAMIC MODEL

After analysis of important energy flows in the controlled room (see Fig. 5, 4) and analysis of available modeling software [9, 10] the model according to *Glück* [11] has been selected as the base for further developments [12].

The selection criteria were the possibility to calculate the distributed thermal parameter in the room, the possibility to calculate all radiation as well as convective and conduction physics, the ability and right to change code in order to adopt it to the necessary tasks. The model [11] was modified and further developed. It was supplemented with a user-interface, blocks for calculation of solar energy, occupants, electric devices, heat sources, etc. The sample realization of the model is shown in Fig 6. Now the modified model is consisting of more than 50 functions and takes ca. 30 MB place.

The basics of the modified thermodynamic model are simplified finite difference method (FDM) air volume structure with horizontal layers as volume nodes together with wall structure with mainly vertical layers and division of the wall in nearly similar plane peaces.

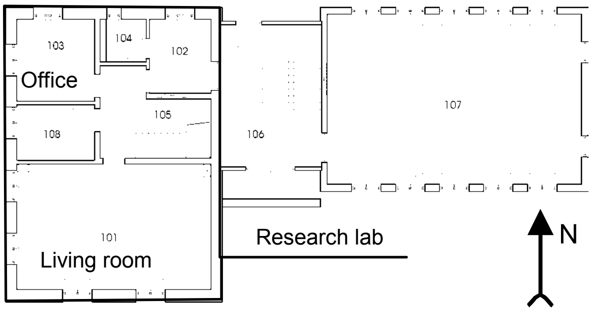

Fig. 4 – plan of research lab SmartHOME at the University of Bundeswehr in Munich (two test rooms are marked).

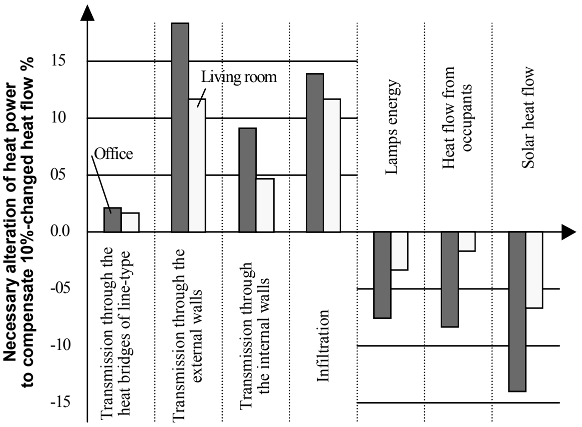

Fig. 5 – Significance of important heat flows in a room. Sample calculations for a real case. ("Office" – small, 10 m², a shade-side room and "Living room" – big, 38 m², a sun-side room. The SmartHOME laboratory at the campus of Universität der Bundeswehr, Munich [13]).

The volume structure parameter can be described due to solving the mass transport continuity (2), 1D Navier-Stokes (3) and energy (4) equations. The simplification is possible due to combination of FDM principles and empirical equations based on resemblance theory. For example convection on vertical plates can be described as in equation (5), where Ra is Rayleigh-number. Meaningful less number of nodes in such models is a condition for the less calculation power, what is important in real time HVAC control.

$$\frac{\partial \rho}{\partial \tau} + w_x \frac{\partial \rho}{\partial x} + w_y \frac{\partial \rho}{\partial y} + w_z \frac{\partial \rho}{\partial z} + \rho\left(\frac{\partial w_x}{\partial x} + \frac{\partial w_y}{\partial y} + \frac{\partial w_z}{\partial z}\right) = 0 \qquad (2)$$

$$\frac{\partial w_x}{\partial \tau} + w_x \frac{\partial w_x}{\partial x} + w_y \frac{\partial w_x}{\partial y} + w_z \frac{\partial w_x}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - g_x + \frac{\eta}{\rho}\left(\frac{\partial^2 w_x}{\partial x^2} + \frac{\partial^2 w_x}{\partial y^2} + \frac{\partial^2 w_x}{\partial z^2}\right) \qquad (3)$$

$$\frac{\partial t}{\partial \tau} + w_x \frac{\partial t}{\partial x} + w_y \frac{\partial t}{\partial y} + w_z \frac{\partial t}{\partial z} = a\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2}\right) \qquad (4)$$

In a difference to a large number of other building models the radiation can be accurately calculated (see equation 6). Thus all main heat transfer mechanisms (conduction, convection, radiation) are implemented in the thermodynamic model. Airflow in the room and short wave radiation through the windows as well as short wave radiation at the outside wall surface are described.

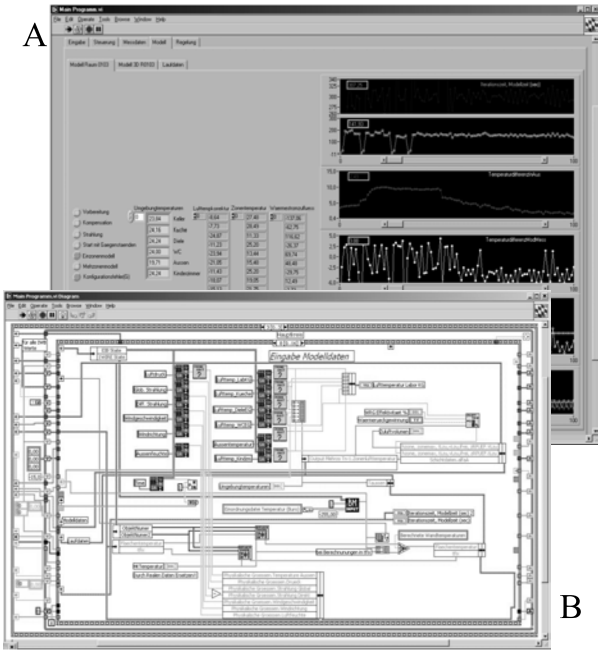

Fig. 6 – Sample of user interface (A) and of model code (B) in visual programming language - G.

$$Nu = \left(0{,}825 + 0{,}387 \cdot Ra^{0{,}167} \cdot \left[1 + \left\langle\frac{0{,}492}{\Pr}\right\rangle^{0{,}563}\right]^{-0{,}296}\right)^2 \qquad (5)$$

$$\begin{bmatrix} 1 & -(1-\varepsilon_2)F_{12} & \cdots & -(1-\varepsilon_{i\max})F_{1i\max} \\ -(1-\varepsilon_1)F_{21} & 1 & \cdots & -(1-\varepsilon_{i\max})F_{2i\max} \\ \vdots & \vdots & \vdots & \vdots \\ -(1-\varepsilon_1)F_{i1} & -(1-\varepsilon_2)F_{i2} & \cdots & -(1-\varepsilon_{i\max})F_{ii\max} \\ \vdots & \vdots & \vdots & \vdots \\ -(1-\varepsilon_1)F_{i\max 1} & -(1-\varepsilon_2)F_{i\max 2} & \cdots & 1 \end{bmatrix} \cdot \begin{bmatrix} \dot{f}_1 + a_{A1} \cdot \dot{f}_{FD} + 0 \\ \dot{f}_2 + a_{A2} \cdot \dot{f}_{FD} + 0 \\ \vdots \\ \dot{f}_i + a_{Ai} \cdot \dot{f}_{FD} + \dot{f}_{FIi} \\ \vdots \\ \dot{f}_{i\max} + a_{Ai\max} \cdot \dot{f}_{FD} + 0 \end{bmatrix} = \begin{bmatrix} \varepsilon_1 \cdot \sigma \cdot T_1^4 \\ \varepsilon_2 \cdot \sigma \cdot T_2^4 \\ \vdots \\ \varepsilon_i \cdot \sigma \cdot T_i^4 \\ \vdots \\ \varepsilon_{i\max} \cdot \sigma \cdot T_{i\max}^4 \end{bmatrix} \qquad (6)$$

The model allows the calculation of distributed and geometry related physical values (for example: temperature at any place, infrared radiation and so on) in the room [14]. On this base the PMV-value can be determined.

The model works as an observer for estimation of the desired values for the control purpose. Some calculation results are presented in Fig. 7.

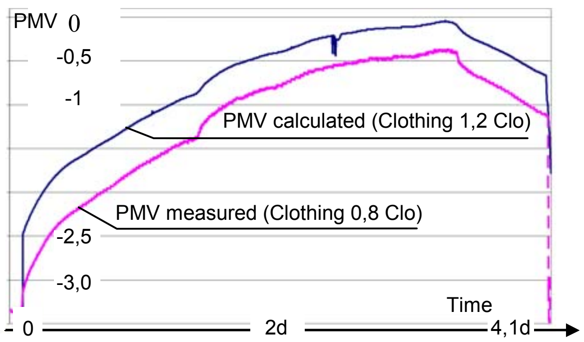

Fig. 7 – calculated heat impulse response for the “Office” room.

4. DISCUSSION

It was particularly mentioned that generally there are two characteristics of a measurement process:

- accuracy
- measurement time (as soon as applied in dynamic system)

For a model-based measurement technique and as it’s base for a given computation device these characteristics are competitive.

Our intentions were to obtain both a suitable precision of the model and the on-line calculation speed using actual computation technologies (PC environment. Pentium-IV – 1,5 Ghz., 500 MB RIMM 400 Mhz. FSB, SCSI - 160). The precision is necessary for thermal comfort control without significant unsuspected deviations for controlled values. The calculation speed is necessary for dynamic process control, what occur because of demand-adjusted HVAC strategy.

Computation algorithm as part of computation device can set free some computation capacity. Thus thin computation algorithm is the only possibility to improve one or both characteristics of the model-based measurement process. Therefore generally two experiment types were considered in accordance with our goals: a precision run and a speed run of the model. The realization of instrumental environment (use of data banks) allows the model to work in on-line as well in off-line mode to adjust the input data flow on calculation speed according to the task.

For a numeric solver the on-line calculation speed means that the whole calculation process should be enclosed in one time step of the control system. Experiments have shown that for a typical room in private sector the smallest significant time constant is more than 10 min. (600 sec.) The smallest time constant depends mainly on heat capacity of enclosed air volume, windows and furniture heat capacity (see Fig. 8). These seem to be nearly similar in most cases.

Another influencing parameter is heating power. The more power, the smaller significant time of the meaningful thermodynamic state changing (temperature raising time) is. Although in a future dynamic HVAC systems typical heating power will be bigger than today [15] actual HVAC systems trends to the smaller power. It means that typical characteristic for the “steady state” control (i.e. the system time) will be appropriate for the actual technical state. Therefore in our actual system the time step is 5 min.

The model precision cannot be better than a precision of the measured data, which is obtained to validate the model. In our case the normal temperature sensors have less than 0,5 grad precision. According this the PMV value cannot be measured better than the 0,26 index precision that varies depending on temperature values up to 0,4 index precision. It corresponds to 7-20 % PPD precision (see Fig. 9).

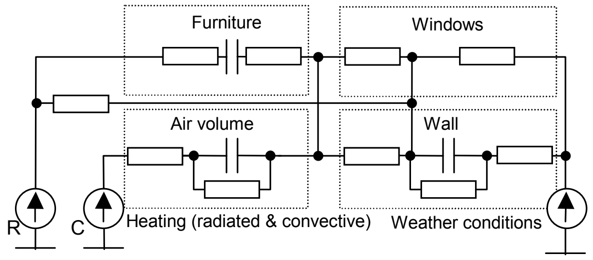

Fig. 8 – Simplified equivalent schema for the thermodynamic building structure.

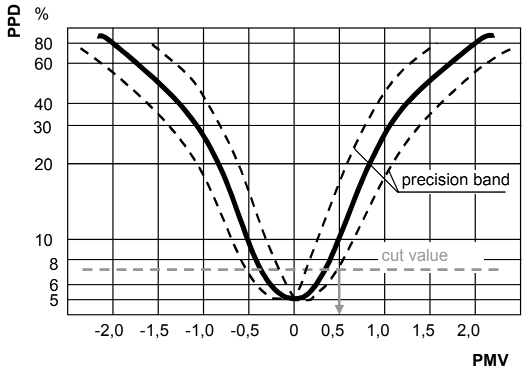

Fig. 9 – Predicted Percentage of Dissatisfied (PPD) as function of predicted mean vote (PMV) [16] and its precision band according to measurement data precision.

The real model precision mainly depends not only on measured data accuracy but also on the realization. Some critical criteria are number of air as well as radiation nodes. As reminder: radiation nodes are divisions of all surfaces in the room, the smaller the divisions are, the bigger is number of radiation nodes, the more equation (more than nodes^2) should be calculated; air nodes are volume divisions in the room and are as layers represented.

It seems to be important to have a maximum number of nodes in order to decrease the calculation error. On the other side a big number of nodes is a challenge for used solver. Sometimes (f.e. 332 radiation nodes and 10 air nodes) it leads to temporarily diverging calculation results through the sub-optimums. The normal convergence is shown in Fig. 10.

The used solver is based on a simple one-dimensional iterative solution technique (method of successive approximations). In order to solve more-dimensional problem one more iterative approach is used (i.e. one iterative process enclosure the other one). The assumption in using of this technique was, that in dynamic process where some system states in neighbor time steps are quite similar, the whole number of iterations could be speeded upon the time steps (see Fig. 11).

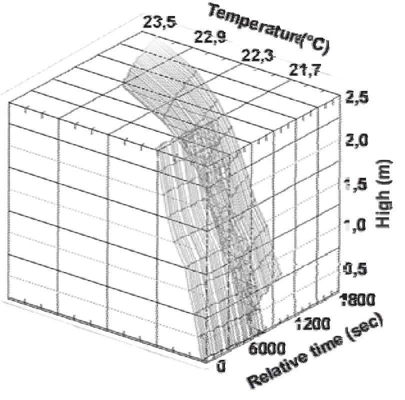

Fig. 10 – Solver results for the air temperature as heat impulse response in the middle of the office room with optimal amount of nodes.

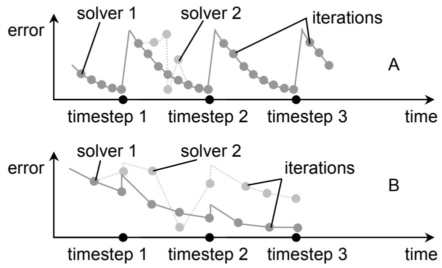

Fig. 11 – Spread iteration solver (B) reduces required computation capacity by iterative approach (A). Dynamic conditions can disallow bad quality solver (solver 2) to converge results.

In order to improve the modeling technique some better solver algorithm should be implemented in the used model [11]. Theoretically the used method of successive approximations requires computation capacity as well as structural redundancy [17]. This can be avoided to improve model-based measurement process for better accuracy or hardware requirements. Than it will be possible to use the on-line modeling with standard PC or embedded PC environment in real world applications.

Some results of discussed research activities are shown in the Table 1.

Table 1. Typical characteristics of investigated model-based measurement technique (air temperature calculation in the middle of the office room).

N	Calculation time, S pro step	Convergence or Error	Nodes (rad., air)
1	187 ±6	No	156, 10
2	830 ± 50	+ 2°C ÷ -6 °C	332, 10
3	470 ÷ 260	± 0,1 °C	332, 10

In order to improve model-based measurement technique a “thin”-modeling consists (besides of the algorithm) of operator data entries. Now the deck-file for the described model is about some thousands of code-lines. To control it for the normal technician becomes to be a challenge. In the next studies the possibility to reduce input data should be investigated.

5. CONCLUSIONS AND OUTLOOK

The presented work studied the possibility of estimate thermal values, which are difficult to measure without troubles for the occupants. The main attention was paid to values, such as thermal comfort.

The analysis has shown that complex thermodynamic modeling can be used to reduce the total costs of demand-driven decentralized HVAC systems. The method is expensive in the stage of model development but cheap, when generally applied in the building industry.

The first computation results have shown the principal functionality of the suggested model-based measurement method. The accuracy of developed model is enough for the HVAC system.

Further research activities should concern the principal possibilities of “thin”-model developing without accuracy loss. Some special notes should be made for long time stability and convergence of the applied modeling techniques.

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