Thermal Modelling and Temperature Control of a House

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Abstract: HVAC (Heating, Ventilation and Air Conditioning) systems used for heating or cooling buildings, consume a considerable amount of energy. To optimize the energy consumption there are important some aspects as: the use of an adequate mathematical model of the building and efficient techniques of automatic control in the regulation of thermal zone temperature and humidity, analysis of the thermal and visual comfort, methods to change behaviour of the occupants etc. As a result it is possible to provide information and suggestions to occupants. This paper presents solutions in modelling, parameter identification and control of the thermal energy in a house.

Keywords: modelling, parameter estimation, control, building, comfort, energy, optimisation.

1. INTRODUCTION

Reducing and optimization of the energy consumption in the residential sector is an important issue in the context of the global warming effect. It is important the modelling and simulation of the houses (thermal, appliances, lighting, comfort, etc.) and optimization of the energy consumption. The DEHEMS project (DEHEMS, 2010) proposes a low budget optimization of the energy consumption in current households. There are several important aspects which have to be taken into consideration and can lead to the reduction of the energy consumption: thermal model; experimental identification; modelling of HVAC systems; environment model, solar radiation and temperature, occupants; including of the electrical appliances in the model; indoor comfort, thermal comfort, visual comfort, indoor air quality; the changing of the user behaviour.

2. THERMAL MODEL

Usually, the models are obtained based on a full description of the building features (white-box), based on an identification process (black-box) or combination of the two (grey-box). The white-box model is preferred when the evaluation of the influence of the modification of the construction materials, or some specific variables on the hydrothermal behavior of the building is needed, or if energy performance improvements and variations in the internal gains exist. These models are obtained based on the energy conservation laws and mass balances. The majority of the simulation programs e.g. (EnergyPlus, 2010), (ESP-r, 2010), (TRNSYS, 2010) etc., use a physical model (white-box). For control purpose, a solution is to use a simplified approach that will stimulate the building linked to a HVAC system, especially in the design stage, when different design schemes can be taken into consideration (Freire et al, 2008). By simplifying the building models, the closed control systems can be implemented and tested in a relatively cheaper way. One of the causes of discomfort to the occupants can be poor quality control systems. It’s estimated that 20-50% of energy in buildings is lost, and 15% of this is due to poor control systems or ineffectively configured, Freire et al (2008).

In this paper it is used a simplified zone thermal model which was originally introduced in Crabb et al (1987): the model has two dynamic temperature nodes roughly representing the air and a lumped structure node, Zhang et al (2005):

\[ C_a \frac{dT_a}{dt} = Q - K_a(T_o - T_a) - K_f(T_a - T_s) \]  (1)

\[ C_w \frac{dT_w}{dt} = K_i(T_a - T_w) - K_o(T_w - T_s) \]  (2)

where \( T_a \) is the air temperature (ºC), \( T_w \) is mean wall temperature (ºC), \( T_o \) is outside air temperature (ºC), \( Q \) is heat input to the air node (kW).

The model uses five parameters: \( C_a \) (kJ/K) is the thermal capacity of the air in the zone, together with other fast-response elements, \( C_w \) (kJ/K) represents the lumped thermal capacitance of the structure, \( K_f \) (kW/K) is the fast conductance ascribed to ventilation and elements with little thermal capacitance e.g. windows, \( K_i \) (kW/K) is the conductance between the air and structure nodes, \( K_o \) (kW/K) is the conductance between the structure node and the outside air. The identification of the 5 parameters allows us to obtain a direct physical interpretation which leads to a strong advantage. Using the model obtained, the user can simulate different thermal scenarios. Also information can be obtained for solutions to reduce energy consumption. To simulate the existing control system, we have used a predictive control algorithm and a parametric model of a black-box type. The parameters of the grey-box type model described by the equations (1), (2) will be identified based on the analysis of input-output data (indoor and outdoor temperature, consumption). We will present two solutions that allow the
identification of parameters of grey-box type model represented by equations (1), (2). In the first variant, the aim is to seek relationships between parameters of the model by choosing an appropriate reference signal. This variant of calculation is very sensitive to noise and, from a practical point of view, if a filtering solution is not used, it is not feasible (Balan et al, 2011). The second option - search based on simulation and optimization, involves knowing every step of sampling the following values: $T_a(t), T_w(t), T_o(t)$ and $Q(t)$. First, it is supposed that $T_w(t)$ is measured. This data is memorized for a number of $n_{sim}$ previous steps of sampling. Therefore at each sampling step it will be possible to simulate the evolution of the process, using as initial data the information of $(t - n_{sim}, T)$ sampling. The simulation will use the current values of estimated parameters $(\hat{C}_{ae}, \hat{C}_{we}, \hat{K}_f, \hat{K}_{ie}, \hat{K}_{oe})$. A performance index is defined to compare the evolution of the measured internal temperature $T_a(t)$ and measured energy consumption $Q(t)$ by the evolution obtained by simulation based on estimated parameters $(\hat{C}_{ae}, \hat{C}_{we}, \hat{K}_f, \hat{K}_{ie}, \hat{K}_{oe})$. If temperatures $T_a(t), T_w(t), T_o(t)$ and the estimations of the parameters of the model are known, then the model of the process can be used to obtain estimation of the energy consumption. This estimate is important when the heat consumption is not measured or, even if it is measured, this consumption is read from time to time, usually at one month intervals, and instant readings are not available. Unlike the measurement of electrical consumption (which involves using a hardware interface component which is relatively cheap), instantaneous measurement of gas consumption can be more expensive and usually involves invasive solutions.

3. THERMAL COMFORT

Thermal comfort has a great weight on the energy efficiency and also on the satisfaction of indoor building occupants. The relations between occupants and the thermal environment are multifaceted and have been the subject of much study, Freire et al (2008), Fanger (1970), Gagge et al (1986), Smith (1991). A large number of thermal comfort indices have been established for indoor climate analysis and HVAC control system design. One of them is the PMV (Predicted Mean Vote), proposed in Fanger (1970). Such index considers environmental variables and individual factors and the closer to zero the PMV value, the better the occupants’ thermal comfort sensation. In Lee (2008) it was proposed a novel sensor network, powered by the artificial light, which was constructed to achieve wireless power transfer and wireless data communications for thermal comfort measurements. Associated to the thermal comfort concept, energy consumption is another important issue related to HVAC systems performance. According to Salsbury (2005), in the United States and other developed countries, about one third of all energy use can be attributed to buildings.

From the work of Fanger given in Guan et al (2003), the PMV index can be written as a nonlinear function of four environmental variables (air temperature $T_a$, relative humidity $\phi$, mean radiant temperature $T_r$ and air velocity $V_a$) and two individual parameters (metabolic rate $M$ and cloth index $I_c$), as follows:

$$PMV = G(T_a, \phi, T_r, V_a, M, I_c)$$

Table 1 shows the relationship among PMV, PPD (Predicted Percentage of Dissatisfied) and thermal sensation.

<table>
<thead>
<tr>
<th>PMV</th>
<th>Thermal Sensation</th>
<th>PPD(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
<td>Hot</td>
<td>100</td>
</tr>
<tr>
<td>+2</td>
<td>Warm</td>
<td>75</td>
</tr>
<tr>
<td>+1</td>
<td>Slightly warm</td>
<td>25</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
<td>5</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
<td>25</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
<td>75</td>
</tr>
<tr>
<td>-3</td>
<td>Cold</td>
<td>100</td>
</tr>
</tbody>
</table>

4. CONTROL ALGORITHM

Both in the case of the heating systems and as well in the case of cooling systems in the residential buildings it is asked the problem of optimization of the energy consumption in conditions of maintaining of adequate thermal comfort and eventually of other supplementary conditions like the visual comfort or quality of air, Kummert et al (2005). For example, in the case of the cooling systems – case of the warm regions, a simpler solution that may be used is the usage of the external blinds, Galatà et al (1996) that permits reducing the heating due to the solar radiation but can reduce also the visual comfort. The complexity of the optimization problem lead to usage of the advanced control algorithms classical control algorithms of type PID not giving satisfactory results.

Model based predictive control use a model of the system as well as a prognosis of the future perturbations for computing that control sequence that will lead to a better behavior of the output signal, on a given horizon, according to a performance criterion. Usually the controller uses as an internal model, a simplified variant of the model of the house and HVAC system. The internal model is a key component of the controller since permits the stimulation of the usage of future control sequences and choosing that one considered optimal. From the computational reasons, usually it is used a simplified variant of the house model and HVAC system.

The performance index (cost function) has to be the expression of a compromise between comfort and energy consumption. The variant in which looks more efficient is the one in which is taken into account the direct predictive control of the thermal comfort, Freire et al (2007). It is needed statistical and deterministic characterization of the presence and activity of the occupants, Clevenger et al (2005).
5. SIMULATION EXAMPLES

First, in equations (1) and (2) we will consider the next values of the process parameters: $C_w = 1400$, $C_{ic} = 2200$, $K_f = 0.02$, $K_e = 1.4$, $K_{ic} = 0.02$ and the initial estimate: $C_{ic} = 2500$, $C_{wc} = 500$, $K_{fe} = 0.05$, $K_{ie} = 2$, $K_{ic} = 0.1$. These values correspond to a type of small studio apartment. It is considered that the maximum power is 4 kW. Chosen sampling period is $T = 60$ s. The results are presented in Fig. 1 (parameter identification) and Fig. 2 (the evolution of temperatures, control signal and control signal estimation).

In Fig. 3 the humidity has a sine shape between 0 and 1. Based on the value of the setpoint for PMV and based on the value of humidity it can be observed that the effect, from the consumed thermal energy point of view, is significant.

In Fig. 4 the metabolism varies in a sine wave between 50 and 100 (the domain for accepted values in the literature is 47-175) and the setpoint for PMV is -0.5. To maintain the PMV value at a constant, the variation of the metabolism makes the right modifications of the air temperature necessary which determines the energy consumption.

In Fig. 5 the clothing parameter varies in a sine wave between 0 and 1.5 (the domain for accepted values in the literature is 0-1.5) and the PMV setpoint is -0.5. To maintain the PMV value at a constant, the variation of the clothing parameter makes the right modification of the air temperature necessary, which determines the energy consumption.

Another test that was made is a variation in sine waves of the PMV setpoint between -0.5 and 0.5 and the examination of the effect on the interior temperature and implicitly on the consumption (Fig. 6).
6. CONCLUSIONS

For reducing of the thermal energy consumed in a house by changing the behavior of the occupants, it is necessary to create a simulator which includes different scenarios of using of the thermal energy and also to provide users with solutions to reduce the energy usage. This paper presents solutions for the modeling and for the experimental identification of the parameters of the model and also solutions for the estimation of energy consumption. As a result, the model can be used to provide information and suggestions on questions related with optimization of energy consumption.

The developed simulator also includes a control algorithm based on the model. Control signal is derived from a set of rules.

The solutions presented to identify the parameters of the model require the measurement of the external mean wall temperature. Given the need for non-invasive measurement systems, it is necessary to find solutions that do not require measuring of this temperature. This is a future work. Some tests show that, without measuring the external mean wall temperature, it is possible to estimate energy consumption and some parameters of the model.

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