REAL-TIME IMPLEMENTATION OF PID-BASED THERMAL COMFORT CONTROL ALGORITHMS

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Abstract. *The present paper is focused on thermal comfort control for building occupants. Thermal comfort is a concept difficult to define and, here, the PMV index is used for such measurement. Based on such index, two strategies are proposed and compared. The first one includes the PMV model in the feedback loop, acting as a PMV sensor. The second is based on generating a temperature set-point signal that optimizes the building (single zone) internal PMV value. Both control loops analyzed are implemented by using PID control laws. An actual environment set-up and a heater device for testing such strategies are presented and experimental results illustrate the performance of the thermal comfort control strategies.*

Keywords: *Thermal Comfort, PMV Control, HVAC, Optimization, PID Control*

1. INTRODUCTION

Energy efficiency in buildings is nowadays an important issue due to the growth of energy costs, energy consumption and environmental impacts. However, there is a trade-off between energy consumption and indoor thermal comfort, which relevance has progressively attracted the attention of industrial and academical research since early 70's. In fact, people spend most of their lifetime in indoor environments and the lack of indoor comfort has a direct effect on their productivity and satisfaction. Therefore, the aim is to save energy while maintaining the occupants' thermal comfort.

A relevant problem in such context is the case where a single HVAC (Heating, Ventilating and Air Conditioning System) device, for instance, an heater or an air conditioning system is present. That is, the case where it is not possible to act independently on two indoor psychometric variables.

On the other hand, thermal comfort in buildings is a concept difficult to define. Over the last decades, a large number of thermal comfort indices have been established for indoor climate analysis and HVAC control system design (Fanger, 1970, Sherman, 1985, Gagge *et al.*, 1986, ASHRAE, 1993). Fanger, in (Fanger, 1970), proposed a criterion that is not only based on temperature and Relative Humidity (RH), but also includes mean radiant temperature, air velocity and individual factors such as metabolism rate and thermal resistance of clothing. An index based on all these variables, the PMV (Predicted Mean Vote), is obtained and the closer to zero is the PMV value, the better will be the occupants' thermal comfort sensation.

A majority of HVAC control systems are still considered as temperature control problems, but there are some solutions proposed in the literature that searche to improve the building occupants' thermal comfort. These approaches can be divided into two groups: the ones that deal with temperature signal (eventually, also RH) and those that use the PMV concept.

Some works related to the first approach are recalled in the following. In (Dumur and Boucher, 1994), a strategy to anticipate future changes on the temperature set-point value is proposed in order to keep this signal as close as possible to the set-point. This strategy, first tested in PID's is then proposed in a GPC (Generalized Predictive Control) environment. Usually for the thermal comfort sensation, it might be enough just setting a temperature band value instead of having a temperature regulation control in a precise preset value (Fanger, 1970). By using a fuzzy logic type control law, this characteristic is then used in (Oliveira *et al.*, 2003) by modifying the controller membership functions to include such a band. In (Freire *et al.*, 2005, Freire, 2006), this idea is also explored in the predictive control context.

However, not only temperature has to be controlled, but also the indoor RH and the air velocity to promote thermal comfort. An idea in this context is to assume a PMV sensor, that is, the PMV is a measured controlled variable that is part of an ordinary closed-loop structure (see (Kolokotsa *et al.*, 2001), (Gouda *et al.*, 2001) and (Donaisky *et al.*, 2006), for instance). In (Donaisky *et al.*, 2006), two approaches for dealing with PMV control are present, based on PID and Fuzzy control laws. The first one includes the PMV model in the feedback loop, acting as a PMV sensor, while the second one is based on generating a temperature set-point signal that optimizes the building internal PMV value.

The present paper expands the concepts found in (Donaisky *et al.*, 2006) by presenting *i)* an actual environment for testing thermal comfort controllers *ii)* experimental results of PMV feedback control and optimal set-point generation for thermal comfort control.

The paper is organized as follows. In the next section, concepts related to thermal comfort are reviewed. In Section 3, the first proposed PID controller is presented. Section 4 shows the methodology for set-point generation for PID controllers. In Section 5, the environmental set-up and the experimental results are presented. These results are conducted in the city of Almirante Tamandaré, Paraná, Brazil. Finally, in Section 6, the conclusions are addressed.

2. THERMAL COMFORT

Definition and control of indoor conditions for reaching thermal comfort in buildings are difficult to be established. Thermal satisfaction depends on many parameters - due to all sensible and latent conductive, advective and radiative heat transfer processes that govern the thermodynamic state of occupants' bodies - so that research works on thermal comfort have been conducted and some comfort indices have been proposed over the last decades.

Among the thermal comfort indices presented in academic researches, the most recognized one is the PMV. This index (PMV), is based on a theoretical model combined with the results from experiments with approximately 1300 individuals (Fanger, 1970), and is given by:

$$\begin{aligned} PMV &= F(T_{\rm bs}, T_{\rm cl}, T_{\rm rm}, h_{\rm c}, f_{\rm cl}, M, W, p_{\rm V}) \\ PMV &= (0.303{\rm e}^{-0.036{\rm M}} + 0.028)\{({\rm M}-{\rm W}) - 3.05\times 10^{-3}[5733 - 6.99({\rm M}-{\rm W}) - {\rm p_V}]\} \\ &\quad -0.42[(M-W) - 58.15] - [1.7\times 10^{-5}M(5867 - p_{\rm V})] - [0.0014M(34 - T_{\rm bs})] \\ &\quad -\{3.69\times 10^{-8} f_{\rm cl}[(T_{\rm cl}+273)^4 - (T_{\rm rm}+273)^4]\} - [f_{\rm cl} h_{\rm c}(T_{\rm cl} - T_{\rm bs})] \end{aligned} \quad (1)$$

where $T_{\rm bs}$ is the dry-bulb temperature (^OC) or just indoor air temperature, $T_{\rm cl}$ is the clothing surface temperature (^OC), $T_{\rm rm}$ is the mean radiant temperature (^OC), $h_{\rm c}$ is the convective heat transfer coefficient (W/m^2K) that is calculated as shown by Eq. (2) when the air velocity $v \leq 2.6\ m/s$.

$$h_{\rm c} = 10.4\sqrt{v}, \text{ for } v < 2.6 m/s \quad (2)$$

$f_{\rm cl}$ is the clothing area factor, that is the ratio between the surface area of a clothed body and the surface area of the naked body. $f_{\rm cl}$ is a function of $I_{\rm cl}$, the clothing index. M is the metabolic rate, the rate of transformation of chemical energy into heat and mechanical work by aerobic and anaerobic activities within the body (W/m^2) and W is the effective mechanical power (W/m^2).

The vapor pressure and humidity ratio are correlated as follows:

$$w = 0.622\frac{p_{\rm V}}{p_{\rm T} - p_{\rm V}} \quad (3)$$

where p_T is the local barometric pressure. The term $p_{\rm V}$ can be defined as partial vapor pressure (kPa) and is related to the dry-bulb temperature $T_{\rm bs}$ and RH ϕ (%) as follows:

$$p_{\rm V} = \phi P_{\rm SAT}(T_{\rm bs}) \quad (4)$$

where the water vapor saturation pressure function $P_{\rm SAT}$ is defined, for instance, in (ASHRAE, 1993). The term $T_{\rm cl}$ can be computed iteratively by using thermal resistance of the clothing ($I_{\rm cl}$) and the following equation:

$$T_{\rm cl} = 35.7 - 0.032M - 0.18I_{\rm cl}(3.4f_{\rm cl}\times((T_{\rm cl}+273)^4 - (T_{\rm rm+273})^4) + f_{\rm cl}h_{\rm c}(T_{\rm cl} - T_{\rm bs}) \quad (5)$$

Therefore, combining Eqs. (1) to (5), the PMV index can be written as a function of four environmental variables (temperature: $T_{\rm bs}$, RH: ϕ, mean radiant temperature: $T_{\rm rm}$ and air velocity: v) and two individual parameters (metabolic rate: M and clothing index: $I_{\rm cl}$), as follows:

$$PMV = G(T_{\rm bs}, \phi, T_{\rm rm}, v, M, I_{\rm cl}) \quad (6)$$

Table 1 shows the relationship between PMV and thermal sensation, together with the PPD (Predicted Percentage of Dissatisfied) value. In 1994, the PMV formulae was included in ISO Standard 7730 and a PMV bounds [−0.5,+0.5] has been established as acceptable for thermal comfort in air-conditioned environments.

Table 1. Relationship between PMV, PPD and thermal sensation.

PMV	Thermal sensation	PPD (%)
+3	Hot	100
+2	Warm	75
+1	Slightly warm	25
0	Neutral	5
-1	Slightly cool	25
-2	Cool	75
-3	Cold	100

3. PMV FEEDBACK FOR THERMAL COMFORT CONTROL

The idea of using PMV model in PID control loops is summarized by Fig. 1, which contains the system's block diagram.

In this figure, the control law acts on the PMV error, computed as the difference between the ideal PMV value, i.e. PMV equal to zero and the measured one. As discussed in the previous section, the PMV is computed based on individual and environmental parameters. Therefore, for such calculations, the individual parameters are assumed supplied by the user, depending on the occupants pattern of activity and clothing. Three of the four environmental parameters are measured by temperature, RH and air velocity sensors; and the fourth, i.e., the mean radiant temperature, is set equal to the measured air temperature. The subject of sensing PMV for control purposes is discussed in (Trebien *et al.*, 2006, Trebien *et al.*, 2007).

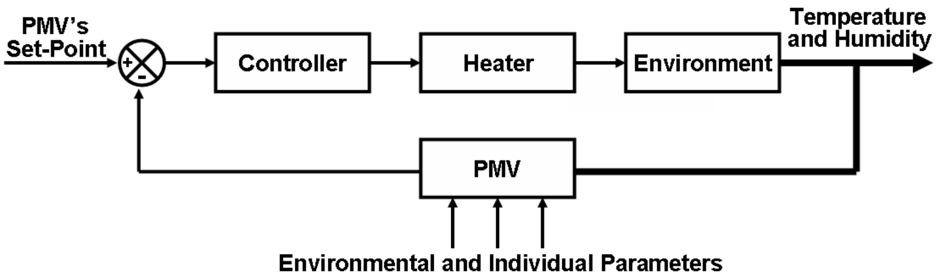

Figure 1. Closed Loop control using PMV feedback.

In the present paper, the control law is based on the well know PID algorithm (Astrom and Hagglund, 1995). The discrete time version of such algorithm, by using backward approximation is given by:

$$U(z) = \frac{c_0 z^2 + c_1 z + c_2}{z(z-1)} E(z) \tag{7}$$

where, c_0, c_1 and c_2 are given by:
$c_0 = K_p + K_d/\Delta t$,
$c_1 = -K_p + K_i \Delta t - 2K_d/\Delta t$ and
$c_2 = K_d/\Delta t$,
and Δt is the sampling period, K_p the proportional gain, K_i the integral gain and K_d the derivative gain of the continuous PID. The signal $e(k)$, i.e., the inverse Z-transform of $E(z)$, is the PMV error, which is given by:

$$e(k) = -y_{\mathrm{PMV}}(k) \tag{8}$$

since the desired PMV value is considered equal to zero; $y_{\mathrm{PMV}}(k)$ is the PMV computed at the discrete time instant k.

4. OPTIMAL TEMPERATURE SET-POINT COMPUTATION FOR THERMAL COMFORT CONTROL

The idea of using a temperature control loop, based on PMV optimization by temperature set-point, is summarized by Fig. 2, which contains the system's block diagram.

In Fig. 2, the control law acts on the temperature error, computed as the difference between the set-point temperature value and the measured temperature, as a standard temperature feedback control. The main point

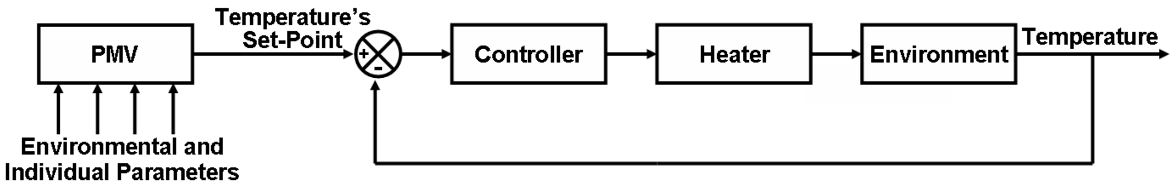

Figure 2. Closed Loop control using optimal set-point generation.

of this approach is that the set-point is not constant, but computed at each sampling time k in order to optimize the PMV environment conditions. This is explained in following. At each instant k, based on the individual parameters supplied by the user and on the temperature, RH and air velocity measurements (as before, the mean radiant temperature is assumed equal to the actual temperature), the optimizer computes the temperature value that would minimize the PMV value for the supplied individual and environmental conditions. Such value is used as temperature set-point. In other words, the following non-linear programming problem is solved at each sampling time:

$$\min_{T_{\mathrm{bs}}} G^2(T_{\mathrm{bs}}, \phi, T_{\mathrm{bs}}, v, M, I_{\mathrm{cl}}) \tag{9}$$

where $G(\cdot)$ is given by Eq. 6. This minimization problem is a non-linear unconstrained optimization problem with one variable, which can be solved by an algorithm like the Golden Section Method (Bazaraa and Shetty, 1979).

The control law can be based on the PID algorithm (Astrom and Hagglund, 1995), as presented in the previous section.

5. EXPERIMENTAL EXAMPLES

In this section the performance of the thermal comfort based control systems considered in the previous sections are analyzed. Therefore, the problem of heating an indoor environment to promote the best possible thermal comfort sensation for the occupants is addressed. The environment set-up and the models for internal temperature and RH are described in the next sub-sections, followed by the presentation of some experimental results related to the control law performances.

5.1 Building and environmental set-up

The environment for testing the thermal comfort controller is a single-zone building possessing the physical dimensions presented in Fig. 3. The building is constructed using materials typically found in Brazil. Inside the thermal zone, there is only one actuator HVAC device, in this case, an oil-heater with the maximum power limited to $1500W$.

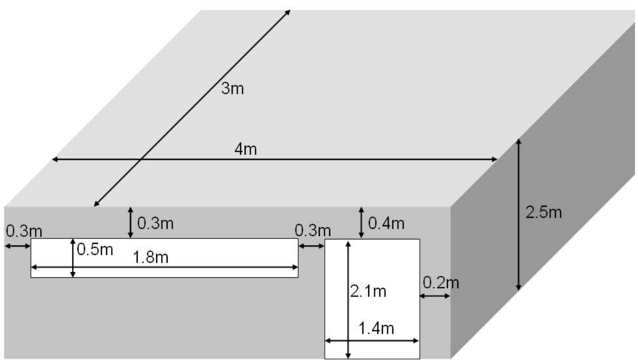

Figure 3. Building dimensions.

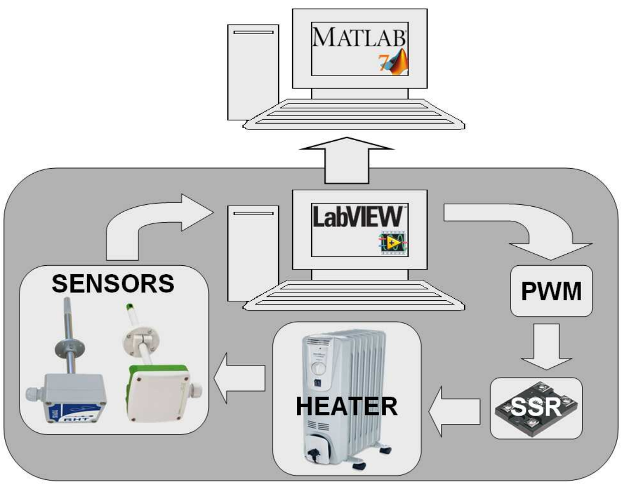

Figure 4. Control loop.

The real-time control implementation is illustrated by Figs 4 and 5. A sensor RHT-DM, made by Novus company, provides measurements for the air temperature and RH, while a sensor EE66, made by Elektronik

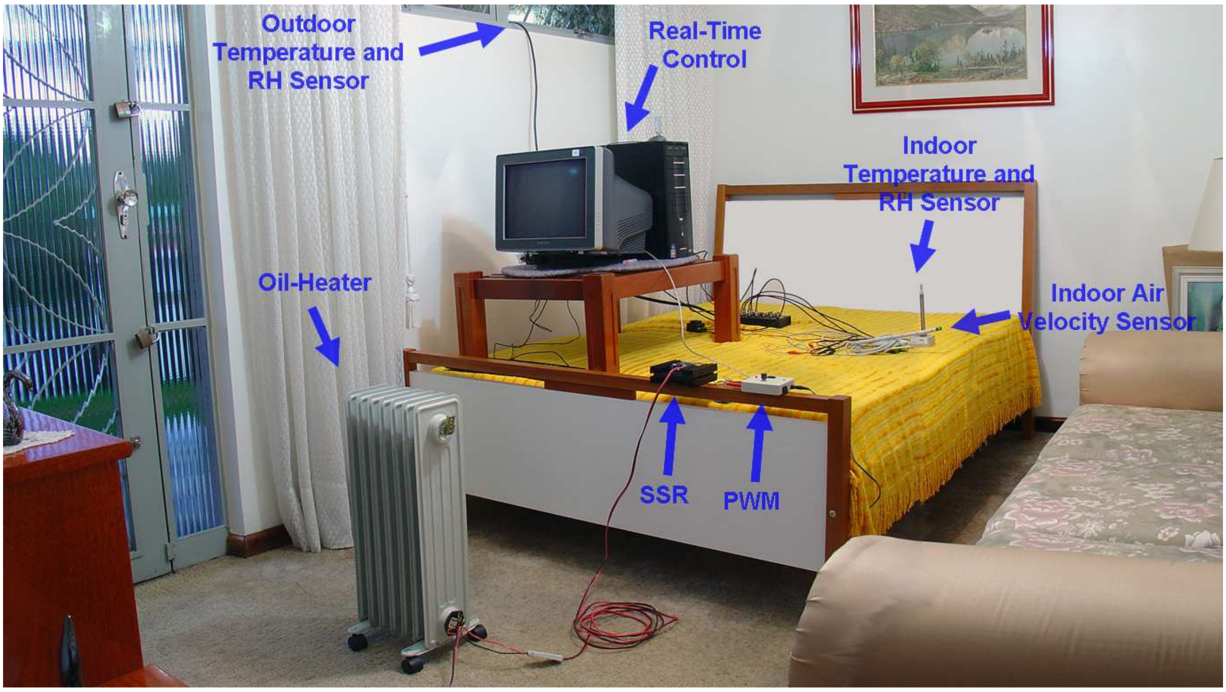

Figure 5. Environmental set-up.

company, measures the air speed. They are used for data acquisition purpose in a LabView's based control loop (NI PCI-6251 hardware). A real-time software, using a sampling time of 20 seconds, makes the PMV calculations based also on the user supplied individual parameters and computes the control law. The computed control signal is modelated by a PWM (Pulse Width Modulation) circuit which acts on a SSR (Solid State Relay) device before reaching the oil heater.

For selecting the PID control parameters, a system identification procedure is performed. By using the system step responses (i.e., by applying a step in the heater power and by measuring the temperature and RH responses) two FOPDT (First-Order Plus Dead-Time) models (Bi *et al.*, 1999) can be obtained. The identified models are given by:

$$H_{\mathrm{Temp}}(s) = \frac{5.29\mathrm{e}^{140\mathrm{s}}}{7820s+1} \tag{10}$$

$$H_{\mathrm{Humi}}(s) = \frac{-0.116\mathrm{e}^{160\mathrm{s}}}{7700s+1} \tag{11}$$

where $H_{\mathrm{Temp}}(s)$ is the transfer function of the temperature signal in relation to the heater input and $H_{\mathrm{Humi}}(s)$ is the transfer function of the RH signal in relation to the heater input. The actual system step response data are presented in the Fig. 6 together with the simulation of the identified models.

Following, the real-time performance of the controllers described in Sections 3 and 4 are present. The experiments were performed in Almirante Tamandaré - Paraná - Brazil during the nights of April 12 and 13, 2007. Figure 7 shows the outdoor temperature and RH values for those two nights.

5.2 Case 1: PMV feedback for thermal comfort PID control

In this section, the case of a PID controller with PMV feedback, presented in Sec. 3, is analyzed.

Here, it is assumed, for the PMV computations, a metabolic rate equal to $M = 58.15\ W/m^2$ ($M = 1\ Met$) and the clothing index equal to $I_{CL} = 0.1163\ m^2K/W$ ($I_{CL} = 0.75\ Clo$). This is equivalent to consider a seated or person relaxed with light clothes.

For the PID parameters selection, i.e. K_p, K_i and K_d, the PSO (Particle Swarm Optimization) method (Kennedy and Eberhardt, 1995, Donaisky and Coelho, 2006) is applied, in a similar procedure as the one described in (Donaisky *et al.*, 2006).

The PSO is based on simulating the animals social behavior, as bird flocking and fish schooling seeking food or avoiding predators. Thus the individuals of the PSO look for a better problem solution through an information interchange on the search space of better solutions (see more in (Donaisky and Coelho, 2006)).

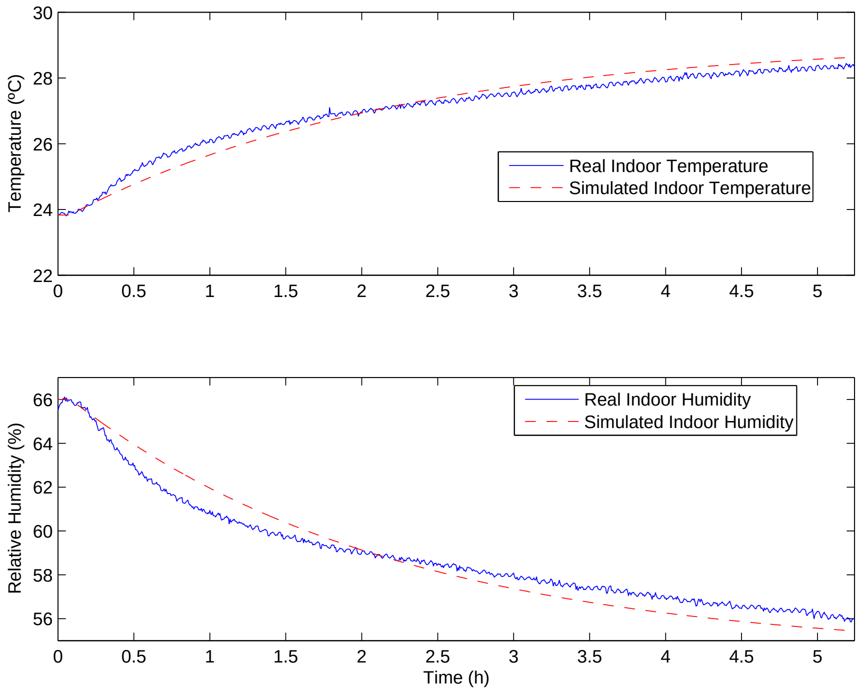

Figure 6. Indoor temperature and RH for identification.

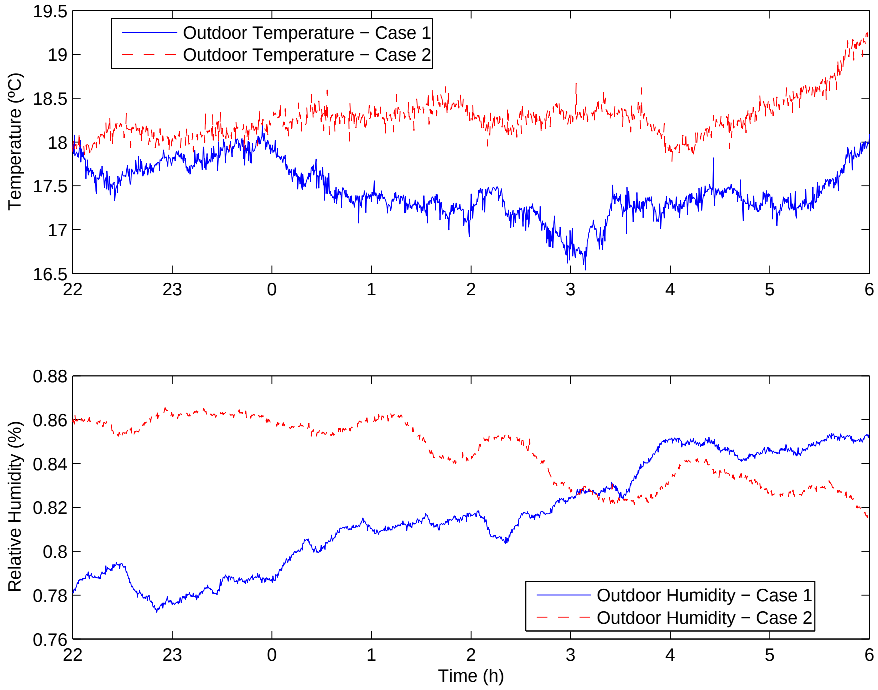

Figure 7. Weather data.

The optimization strategy is based on minimizing, in a simulation environment and for a given PID parameters, the MSE (Mean Square Error) criterion between the output signal (PMV feedback signal) and the set-point signal (equal to zero) by using the identified models. Based on this structure, the PSO iterative algorithm search the PID parameters that minimizes the system MSE.

The computed parameters K_p, K_i and K_d are 17.9088, 0.0281 and 0, respectively.

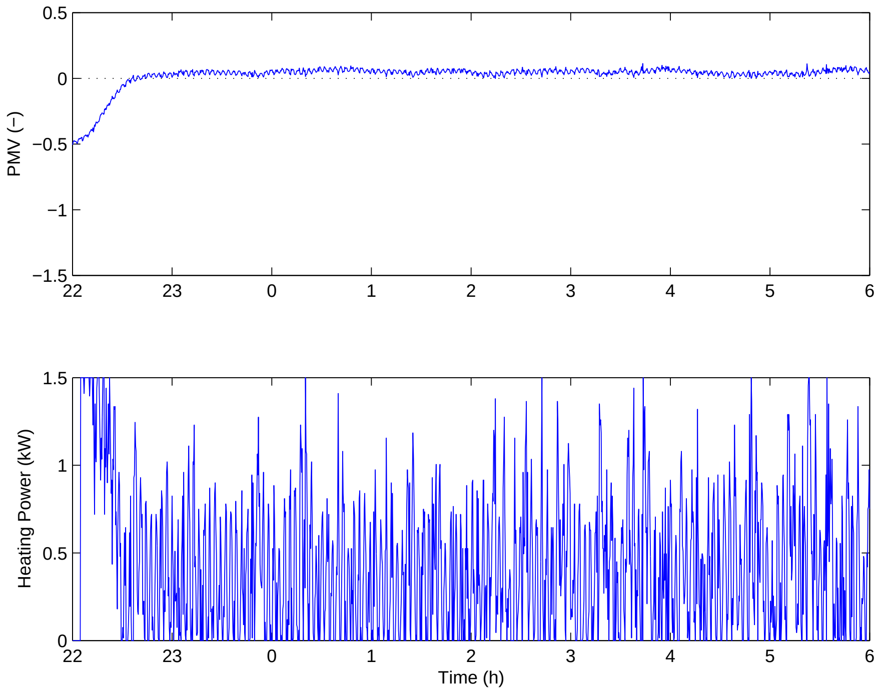

Figure 8. PMV and Control signal for PID controller with PMV feedback.

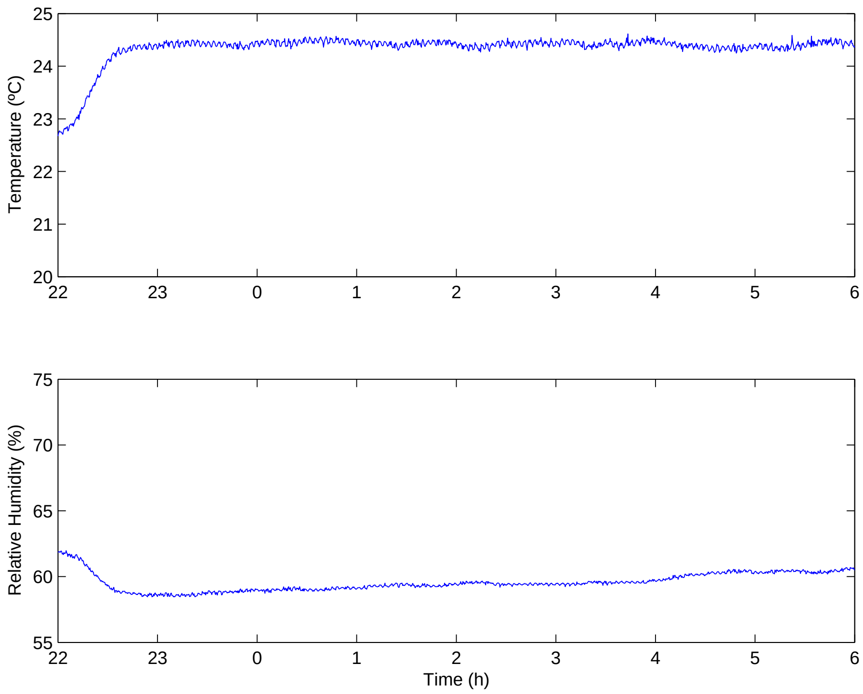

Figure 9. Indoor Temperature and RH for PID controller with PMV feedback.

The real time experiments was conducted during eight hours and the controller was turned on in the first five minutes of such period. The performance of this PID control system is presented in Figs. 8 and 9.

As it can be seen in Fig. 8, the applied control strategy is successful in maintaining the PMV value close to zero during the experiments, which indicates that the indoor thermal comfort sensation is adequate assuming occupants having the pre-defined behavior. Figure 9 shows the indoor hygrothermal conditions during the experiments. The mean square error between the PMV signal and the desired one, computed between 0 and 6 am, is 0.0028. The total energy consumption was $209.92kWh$. During the transient state, the rate of improving the PMV towards to zero is 0.000256 PMV/seconds or close to 1 PMV/hour.

5.3 Case 2: Optimal temperature set-point for thermal comfort PID control

In this section, the case of a PID controller with optimal set-point generation for promoting thermal comfort, presented in Sec. 4, is analyzed.

For the internal loop PID parameters selection, the PSO optimization algorithm is applied. The computed parameters K_p, K_i and K_d are 9.0114, 0.0235 and 0, respectively.

The PMV computations assume that the individual parameters are the same as the ones described in Case 1. Moreover, the golden section method is used for the non-linear optimization. The method proved to be fast enough to find an optimal set-point value at each sampling time, i.e., 20 seconds.

The experiment was conducted during eight hours and the controller is turned on in the first five minutes of such period. The performance of this PID control system is presented in Figs. 10 and 11.

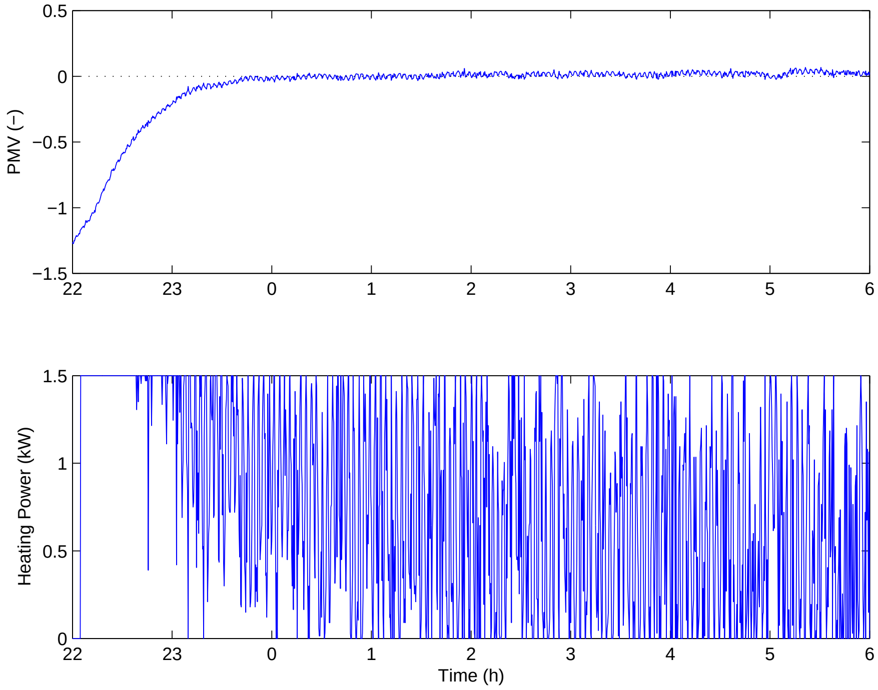

Figure 10. PMV and Control signal for PID controller with Temperature feedback.

As it can be seen in Fig. 10 the applied control strategy is successful in maintaining the PMV value close to zero during the experiments, which indicates that the indoor thermal comfort sensation is adequate assuming occupants having the pre-defined behavior. Figure 11 illustrates the indoor hygrothermal conditions during the experiments. At the top, it can be noticed the set-point generated by the PMV optimizer together with the actual indoor temperature signal. The mean square error between the PMV signal and the desired one, computed between 0 and 6 am, is 0.0005. The total energy consumption was $379.11kWh$. During the transient state, the rate of improving the PMV towards to zero is 0.000276 PMV/seconds or close to 1 PMV/hour as in Case 1.

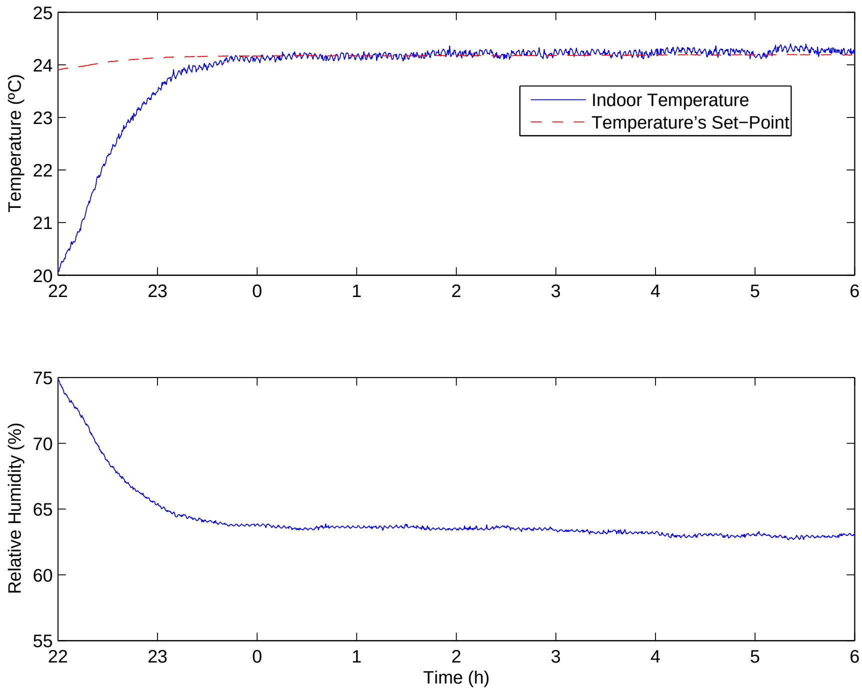

Figure 11. Indoor Temperature and RH for PID controller with Temperature feedback.

6. CONCLUSION

In this paper, the indoor thermal comfort control problem in buildings (single zone) equipped with a single HVAC device has been analyzed. Two control strategies, based on the PID control law, for indoor thermal comfort optimization focused on the PMV index have been presented. Both strategies use explicit PMV computations in the control loop.

In the first case, PMV computation have been made in the feedback of control loop, acting as a PMV sensor. In the second case, PMV model has been used for generating an optimal value for the set-point in an ordinary temperature closed-loop control.

An experimental set-up for thermal comfort real-time controller evaluation was presented. It is based on measuring the environmental relevant variables, a HVAC device and on a hardware for real-time control implementation.

The closed-loop control results, based on PID algorithms optimized by using the PSO method, show that both schemes were able to promote indoor thermal comfort, assuming that the individual parameters supplied by the user were not too far from the reality (see more details in (Trebien *et al.*, 2007)). The numerical results demonstrate that the closed loop performance of the controllers was adequate. By looking at the performance results of both control systems with the $1.5kW$ oil-heater, the PMV feedback strategy presented a slightly worst regulation performance, but consumed less energy. Both presented a similar set-point tracking performance and can improve the indoor PMV at a rate of 1 PMV per hour.

7. ACKNOWLEDGEMENTS

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