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A nonlinear model based predictive control strategy to maintain thermal comfort inside a bioclimatic building

M. Castilla, J.D. Álvarez, J.E. Normey-Rico and F. Rodríguez

Abstract— **People usually spend most of the time inside buildings. Therefore, it is necessary to reach a tradeoff between users' comfort and energy saving. The use of appropriate control strategies can highly contribute to this purpose. This paper presents a practical nonlinear model predictive control strategy, that allows to obtain a high thermal comfort level optimizing the use of an HVAC (Heating, Ventilation and Air Conditioning) system. Simulation results obtained from the application of this strategy to a characteristic room of the CDdI-ARFRISOL-CIESOL building are included and commented.**

I. INTRODUCTION

Nowadays, energy consumption in buildings represents approximately 40% of total energy consumption around the world, more than half used by HVAC (Heating, Ventilation and Air-Conditioning) systems [1], [2], [3]. Hence, energy efficiency, the integration of renewable energies and the suitable use of energy inside buildings, are topics that are being widely studied from both, a scientific and a technical, points of view [4].

In addition, as people usually develop their daily activities inside buildings, saving on energy efficiency must not put users' welfare at risk [5] being necessary to look for a tradeoff between them. In order to achieve this objective, different approaches can be considered, such as the construction of bioclimatic buildings, which incorporate passive strategies and make use of renewable energies. However, in some cases, and mainly due to the typical climate of the location where the building is located, this approach by itself may be insufficient [6]. In these cases, it is necessary to use appropriate control strategies on HVAC systems, with the main objective of providing comfortable environments reducing energy consumption at the same time. In [7] a detailed review about different techniques used to control building users' comfort was done.

In general, MPC (Model Predictive Control) strategies are widespread in the control of industrial processes, and it is one of the used techniques to thermal comfort control [7]. This strategy is characterized by the explicit use of a model of the process to obtain the control signal by minimizing an objective function [8]. Nevertheless, although most MPC applications are based on the use of linear models, generally industrial processes have nonlinear dynamics, as in the case studied in this paper, where a nonlinear model based on first principles is used. In order to deal with these nonlinear dynamics, the main aim of this paper is to present a PNMPC (Practical Non-linear Model based Predictive Control) strategy [9] that ensure thermal comfort inside a certain environment, reducing, at the same time, energy consumption. This strategy has been applied in simulation to a typical room of the CDdI-ARFRISOL-CIESOL bioclimatic building, although the results obtained with these control strategy can be easily extrapolated to any room of a building with a suitable sensor network and an HVAC system.

The paper is organized as follows: Section 2 briefly introduces the CDdI-ARFRISOL-CIESOL building. Section 3 includes an overview of the thermal comfort concept and a brief description of its estimation procedure, the PMV index. In Section 4, the PNMPC control approach is described, and a short description about the model of the room used for simulation is done. Section 5 is devoted to the obtained results. Finally, in Section 6, the main conclusions are summarized.

II. SCOPE OF THE RESEARCH: THE CDDI-ARFRISOL-CIESOL

The CDdI-ARFRISOL-CIESOL research centre on solar energy (http://www.ciesol.es), see Fig. 1, is a mixed centre between CIEMAT and the University of Almería. In addition, it is one of the five CDdI: *"Research demonstrator collector"* studied in the ARFRISOL project (http://www.arfrisol.es), which is a singular strategic project of the Spanish R&D plan 2004-2011 financed by EU-ERDF funds and by the Spanish Ministry of Science and Innovation (MICINN).

This building has a total surface of 1071.91 m^2 divided in two plants, and, it is located inside the campus of the University of Almería in the South East of Spain. This geographic location is characterized by having a typical desert Mediterranean climate, with an annual average number of 2965 hours of sunshine (climate values registered at the meteorologic station of the Almería airport, situated a 3.5 kilometers far from CDdI-ARFRISOL-CIESOL). Moreover, it was built following a bioclimatic architecture criteria, thus, it counts with several passive strategies, a wide sensors network which data are being stored in a database through an acquisition and monitoring system [10] and an HVAC system based on solar cooling [11] that use a solar collectors field, a hot water storage system, a boiler and an absorption machine with its refrigeration tower.

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Fig. 1. CDdI-CIESOL-ARFRISOL building.

III. THERMAL COMFORT

Most part of international standards, such as *ISO 7730* [12] and *ASHRAE 55* [13] define thermal comfort just as: *"That condition of mind which expresses satisfaction with the thermal environment"* [14]. However, by means of this definition it can be inferred that comfort is a cognitive process which depends of different kinds of processes, such as, physical, physiological or even psychological aspects [15].

Furthermore, thermal comfort sensation depends, apart from the air temperature, on several circumstances, such as the season of the year, the place where the human is, how much time he is in, etc. However, different studies performed in this area have demonstrated that the air temperature that people choose for thermal comfort under similar conditions of physical activity, clothing, air velocity and relative humidity is very similar even though climates, living conditions and cultures differ around the world [15].

There exist many indexes in the bibliography to estimate thermal comfort conditions inside a certain environment [16], [17], [18], [19], [20]. However, the most extended index is the PMV (*Predicted Mean Vote*), which is able to predict the average response about thermal sensation of a large group of people exposed to certain thermal conditions for a long time [21]. The value of this index is a seven-point thermal sensation scale: 0 neutral, ±1 slightly warm/cool, ±2 warm/cool, ±3 hot/cold. In addition, PMV index formulation is based on the energy balance of the human body, considering this as a whole entity. Therefore, PMV index can be estimated as a function of this balance and the following six variables: human activity (M), clothing insulation (I_{cl}), air temperature (T_{air}), mean radiant temperature (T_{mr}), air velocity (V_{in}) and air humidity (H_r), just as it is shown in (1).

$$PMV = [0.303\exp(-0.036M) + 0.028] \cdot L \tag{1}$$

In the previous equation, M is the metabolic rate $[W/m^2]$ and L is the thermal load in the human body $[W/m^2]$ defined as the difference between the internal heat production and the heat lost which happens when the person is in a thermal situation, see (2)-(6). More information about the procedure to estimate this index can be found in [22].

$$\begin{aligned} L &= (M-Q) - 0.0014 \cdot M \cdot (34 - T_{air}) \\ &- 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-Q) - p_a] \\ &- 0.42 \cdot (M - Q - 58.15) \\ &- 1.72 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) \\ &- 39.6 \cdot 10^{-9} \cdot f_{cl} \cdot [(T_{cl}+273)^4 - (T_{mr}+273)^4] \\ &- f_{cl} \cdot h_c \cdot (T_{cl} - T_{air}) \end{aligned} \tag{2}$$

where

$$\begin{aligned} T_{cl} &= 35.7 - 0.028(M-Q) \\ &- 0.155 \cdot I_{cl} \cdot [f_{cl} \cdot h_c \cdot (T_{cl} - T_{air}) \\ &+ 39.6 \cdot 10^{-9} \cdot f_{cl} \cdot [(T_{cl}+273)^4 - (T_{mr}+273)^4]] \end{aligned} \tag{3}$$

$$h_c = \begin{cases} 2.38 \cdot (T_{cl} - T_{air})^{0.25}, & A > 12.1 \cdot \sqrt{V_{in}} \\ 12.1 \cdot \sqrt{V_{in}}, & A \leq 12.1 \cdot \sqrt{V_{in}} \end{cases} \tag{4}$$

$$A = 2.38 \cdot (T_{cl} - T_{air})^{0.25} \tag{5}$$

$$f_{cl} = \begin{cases} 1.0 + 0.2 \cdot I_{cl}, & I_{cl} \leq 0.5 \text{ clo} \\ 1.05 + 0.1 \cdot I_{cl}, & I_{cl} > 0.5 \text{ clo} \end{cases} \tag{6}$$

In (2)-(6), p_a is the partial water vapor pressure in the air, T_{cl} is clothing surface temperature and f_{cl} is the clothing area factor. In addition, relative humidity (H_r) can be defined as the relation between partial water vapor pressure in the air and saturated water vapor pressure from a temperature. Hence, to guarantee thermal comfort conditions in a certain environment, international standards recommend to maintain PMV index value at 0 with a tolerance of ±0.5 [23].

IV. CONTROL SYSTEM ARCHITECTURE

After several analysis performed inside the CDdI-CIESOL-ARFRISOL building, it has reached the conclusion that it was necessary to establish a specific control system, able to keep climate conditions inside a comfort zone, and, at the same time, minimizing energy consumption [22].

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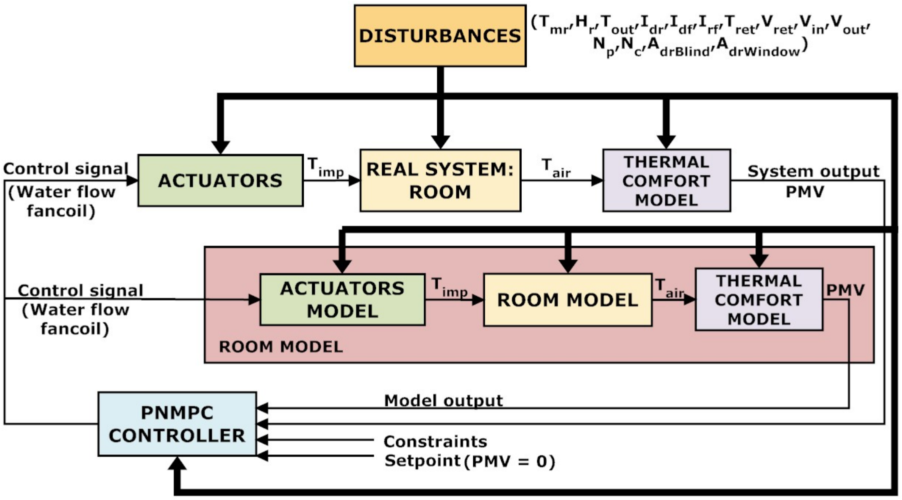

Fig. 2. PNMPC control system architecture.

In a first approach, different control approaches have been compared by means of different cost functions [24]. In these approaches, linearized models around a typical operation point, which represent air temperature dynamic [^oC] as a function of fancoil speed [$\%$], were used. By this way, it is possible to maintain PMV index inside the comfort zone by means of air temperature control.

This section describes a PNMPC control approach used to regulate thermal comfort inside a typical room of a bioclimatic building, see Fig. 2. Thus, the main control objective is to maintain users' thermal comfort inside a zone defined by PMV index (1). To reach this objective, air temperature will follow a temperature setpoint in order to obtain a PMV index equals to zero, since the other variables that influence in the PMV index are considered disturbances. On the other hand, the fancoil will be the physical actuator that will allow air temperature to follow its associated setpoint. As in this preliminary work, the strategy has been only tested in simulation, the selection of a PMV value equals to zero tries to demonstrate that it is possible, with the available resources, to obtain an optimal situation, that is, the maximum users' thermal comfort and, to reduce energy consumption as much as possible.

As it was mentioned previously, this control approach has been tested through several simulations inside a typical room of the CDdI-ARFRISOL-CIESOL. Furthermore, as in [24], it has been considered, that there is only one actuator available to control thermal comfort inside it, the HVAC system based on solar cooling [11]. Thus, it is necessary to characterize its behaviour in order to be used in the proposed control approach. More specifically, in this approach models of the room based on first principles have been developed, as it is shown in Section IV-A.

A. Room Model based on First Principles

To test the control strategy developed in this work, one of the more representative rooms of the building, see Fig. 3, has been chosen. The modeled room is an office located in the upper floor of the building and with a total volume of $4.96 \times 5.53 \times 2.8\ m^3$. It faces to North and is delimited by two rooms with similar characteristics. In addition, it has a window with a total surface of $2.15 \times 2.09\ m^2$ situated in the North wall, and it is equipped with a fancoil unit, that allows to regulate impulse air temperature controlling the amount of water which flows through it.

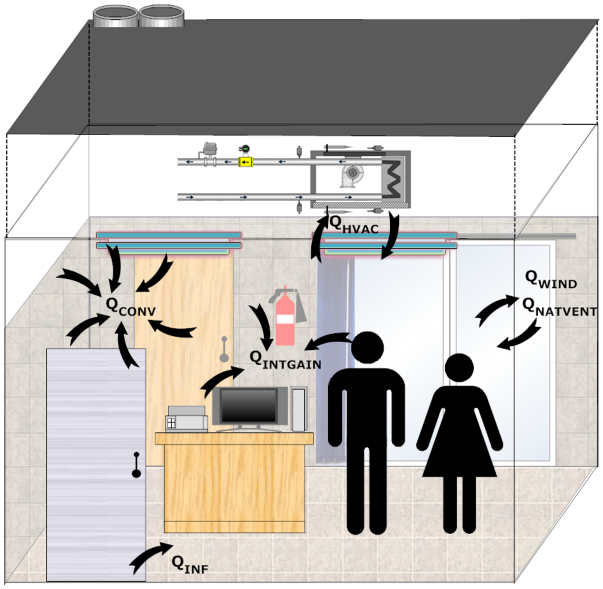

Fig. 3. Modeled room of the CDdI-CIESOL-ARFRISOL building.

Therefore, it has been necessary to develop a model able to represent properly its behaviour. To do that, the room has been considered as a complex system composed of several kinds of elements, such as, walls, windows, the HVAC system, etc. Furthermore, it must be taken into account the outside environmental conditions of the room, like the region climate, the adjacent rooms, etc. After that, the existing relations among different components, and between each of them and the adjacent environment are established using heat transfer (conduction, convection and radiation) and mass transfer laws. A brief description is displayed in (7)-(13) by presenting the balance equations for the indoor air temperature:

$$m_a \cdot Cp_a \cdot \frac{dT_{air}}{dt} = Q_{conv} + Q_{wind} + Q_{HVAC} + Q_{natvent} + Q_{inf} + Q_{intGain} \quad (7)$$

$$Q_{conv} = f(T_{air}, T_N, T_S, T_W, T_E, T_{gr}, T_c) \quad (8)$$

$$Q_{wind} = f(T_{air}, T_{out}, I_{dr}, I_{df}, I_{rf}) \quad (9)$$

$$Q_{HVAC} = f(T_{imp}) \quad (10)$$

$$Q_{natvent} = f(T_{air}, T_{out}) \quad (11)$$

$$Q_{inf} = f(T_{air}, T_{out}) \quad (12)$$

$$Q_{intGain} = f(T_{air}, T_{mr}, H_r, N_p) \quad (13)$$

where

- m_a: air mass $[kg]$.
- Cp_a: air specific heat $[J/kgK]$.
- T_{air}: indoor air temperature $[K]$.
- Q_{conv}: heat gain by free convection through walls $[W]$.
- Q_{wind}: heat gain through the window $[W]$.
- Q_{HVAC}: heat gain by forced ventilation $[W]$.
- $Q_{natvent}$: heat gain by natural ventilation $[W]$.
- Q_{inf}: heat gain due to infiltrations $[W]$.
- $Q_{intGain}$: heat gain due to internal gains (people, electrical appliances, lights, etc.) $[W]$.

Hence, thermal comfort control (PMV) will be performed by the control of the indoor air temperature (T_{air}). This variable will be controlled by means of the air temperature in the fancoil impulse (T_{imp}), which, at the same time, is directly controlled by the water flow in the fancoil. Finally, the main disturbances which have influence on the control process are the plane radiant temperature of the surfaces of the room (T_x), the outdoor air temperature (T_{out}), the irradiance (I_x), the relative humidity (H_r) and the number of people inside the room (N_p).

B. A Nonlinear Model Predictive Control approach

In general, MPC control algorithms, as Generalized Predictive Control (GPC), are applied to linear systems that are characterized by the use of a predicted output data vector, $\widetilde{\mathbf{Y}}$, throughout a prediction horizon, N, as a function of a vector which contains changes in the control action, $\mathbf{\Delta u}$,

$$\widetilde{\mathbf{Y}} = \mathbf{F} + \mathbf{G} \cdot \mathbf{\Delta u} \quad (14)$$

where the system free response vector, $\mathbf{F}$, and the matrix $\mathbf{G}$ are estimated by means of different methods depending of the selected algorithm. It is important to highlight that, $\widehat{\mathbf{Y}} = \mathbf{F}$ is the response obtained if the control actions are equal to zero, whereas, $\widehat{\mathbf{Y}} = \mathbf{G} \cdot \mathbf{\Delta u}$ is the response obtained if the initial conditions, inputs and disturbances, are null. For the problem at hand, the PNMPC strategy proposed in [9] is used to compute both $\mathbf{F}$ and $\mathbf{G}$ from a non-linear model. Such strategy is different from traditional non-linear predictive control techniques since it uses linearized models at each sample time, which are independent of the system operating points, in order to estimate the matrix $\mathbf{G}$, whereas, a non-linear model for $\mathbf{F}$ is calculated doing the control actions equal to zero and assuming no changes in the disturbances through the prediction horizon. Therefore, in this strategy the predicted output data vector, $\widehat{\mathbf{Y}}$ is estimated as it is shown in (15)-(17):

$$\widehat{\mathbf{Y}} = \mathbf{F} + \mathbf{G}_{PNMPC} \cdot \mathbf{\Delta u} \quad (15)$$

$$\mathbf{F} = f(\mathbf{y_p}, \mathbf{\Delta u_p}, \mathbf{\Delta v_p}) \quad (16)$$

$$\mathbf{G}_{PNMPC} = \frac{\partial \widehat{\mathbf{Y}}}{\partial \mathbf{\Delta u}} \quad (17)$$

where $\mathbf{\Delta u_p}$ are the past increments in the control actions, $\mathbf{\Delta v_p}$ are the past increments in the measurable disturbances, $\mathbf{y_p}$ are the past and present system outputs, and $\mathbf{G}_{PNMPC}$ matrix is the Jacobian of $\widehat{\mathbf{Y}}$. This representation can be used with both, linear models and nonlinear models if its states are continuous and differentiable for each input of the system. To estimate $\mathbf{F}$ and $\mathbf{G}_{PNMPC}$ at each sample time it is necessary to use the algorithm presented later and described in [9]. After that, the control law is obtained using techniques similar to the used in classical MPC algorithms.

1) Cost Function: Model Predictive Control (MPC) is characterized by the explicit use of a process model in order to obtain the control signal by minimizing a cost function [8]. In (18), it can be observed the cost function used in the case of study of the CDdI-CIESOL-ARFRISOL building. This cost function tries to find out the best future control signal u, which is able to minimize the tracking error, that can be defined as the difference between the future predicted output (Y_p), the PMV index, and the reference value for this index (**w**). Furthermore, at the same time, the future control action, that is, the water flow through the fancoil unit, is penalized by means of a weighting factor.

$$J = \sum_{j=1}^{N} \delta(j)[Y_p(k+j|k) - w(k+j|k)]^2 + \sum_{j=1}^{N_u} \lambda(j)[u(k+j-1)]^2 \quad (18)$$

where

- N is the prediction horizon.
- N_u is the control horizon.

- $Y_p(k+j|k)$ is the prediction of the output of the system, in this case PMV index, estimated at sample time $k+j$ with the information available at sample time k.
- $w(k+j|k)$ is the future reference for the PMV index.
- $u(k+j-1)$ is the future control signal.
- $\delta(j)$ is the weight associated with the setpoint tracking.
- $\lambda(j)$ is the weight associated with the control signal.

2) Constraints: In addition, the optimization problem is subject to several systems constrains given by (19)-(21). The first constraint (19) limits the maximum and minimum change in the control signal at each sample time. This constraint is used to avoid abrupt changes in the actuator that may cause any failure. The second constraint (20) makes reference to physical hard constraints of the HVAC system, in other words, it takes the inside fancoil water flow saturation $[u_{min}, u_{max}]$ into account. Finally, the third constraint (21), gives the lower limit ($Y_{p_{min}}$) and the upper limit ($Y_{p_{max}}$) of the output variable, that is, the PMV index value.

$$\Delta u_{min} \leq \Delta u(k+j|k) \leq \Delta u_{max} \quad \forall j = 0, \ldots, N_u - 1 \tag{19}$$

$$u_{min} \leq u(k+j|k) \leq u_{max} \quad \forall j = 0, \ldots, N_u - 1 \tag{20}$$

$$Y_{p_{min}} \leq Y_p(k+j|k) \leq Y_{p_{max}} \quad \forall j = 0, \ldots, N - 1 \tag{21}$$

Algorithm 1 Procedure to estimate F and G_{PNMPC}

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Obtain $\widehat{\mathbf{Y}}^0$ vector with a length of $N$, where $N$ is the prediction horizon: to do that, it is necessary to execute the model using past inputs, outputs and measurable disturbances, and with $\mathbf{\Delta u} = [0\ 0\ \ldots\ 0]^T$. $\widehat{\mathbf{Y}}^0 = \mathbf{F}$.
Estimate the first column of the $\mathbf{G}_{PNMPC}$ matrix: as in the previous step, the model has to be executed using past inputs, outputs and measurable disturbances, and, in this case, with $\mathbf{\Delta u} = [\epsilon\ 0\ \ldots\ 0]^T$ where $\epsilon$ is a very little value, such as, $\frac{u(k-1)}{1000}$.
    $\mathbf{G}_{PNMPC}(:,1) = \frac{\widehat{\mathbf{Y}}^1 - \widehat{\mathbf{Y}}^0}{\epsilon}$
Estimate the second column of the $\mathbf{G}_{PNMPC}$ matrix: the model is executed using past inputs and outputs, and, with $\mathbf{\Delta u} = [0\ \epsilon\ 0\ \ldots\ 0]^T$.
    $\mathbf{G}_{PNMPC}(:,2) = \frac{\widehat{\mathbf{Y}}^2 - \widehat{\mathbf{Y}}^0}{\epsilon}$
Continue with the remainder columns of $\mathbf{G}_{PNMPC}$ matrix until the las column where $\mathbf{Y}^{Nu}$ vector is obtained executing the model with past inputs and outputs, and with $\mathbf{\Delta u} = [0\ 0\ \ldots\ \epsilon]^T$, where $Nu$ is the control horizon.
    $\mathbf{G}_{PNMPC}(:,Nu) = \frac{\widehat{\mathbf{Y}}^{Nu} - \widehat{\mathbf{Y}}^0}{\epsilon}$
```

V. RESULTS AND DISCUSSION

The model presented in Section IV-A has been calibrated and validated for a typical office room inside the CDdI-ARFRISOL-CIESOL building, that is, the developed model is used as an indoor temperature simulator for this building. Hence, the previous strategy has been tested in simulation inside the CDdI-ARFRISOL-CIESOL building during a typical day of the summer period. For this day, several tests has been performed with different control signal weighting coefficients (λ) and maintaining the tracking error weighting coefficient (δ). More specifically, different tests had a total duration of five hours, from 9 a.m. to 14 p.m., that is, the typical schedule of an office. The tests were performed with a sample time of 30 s and with a prediction and control horizons equals to five ($N = N_u = 5$). The values selected for these variables were chosen as a function of the faster involved variables dynamic, such as, the indoor air velocity or direct radiation. Hence, the main objective was to find out if the developed strategy was able to maintain thermal comfort under several constraints of energy saving, and to select that control signal weighting coefficient which provides best results.

The results obtained with the different tests performed are shown in Fig. 4. This figure can be divided in four parts: the first graph shows the PMV index evolution. In the second one, the control signal, that is, water flow through fancoil, is shown. Finally, third and fourth graphs represent the dynamical evolution of the most important disturbances that have direct influence on thermal comfort: indoor air temperature, which is estimated by means of the model described in IV-A, and relative humidity, respectively. However, although there are others variables, such as, irradiance, number of people, etc. the dynamic evolution of them is not shown due to the lack of space.

As it is shown in the top graph of the Fig. 4, with all the selected control signal weighting coefficients a PMV index value almost equals to zero is reached. However, the greater differences lie in the water flow consumption, since, there exist variations around 2 l/min in some places. Hence, as it can be observed Fig. 4, the test with a control signal weighting coefficient equals to 0.001 offers similar results in reference to the PMV index, with a maximum water flow consumption of 8 l/min and a mean water flow consumption of 4.76 l/min approximately. Therefore, after an exhaustive analysis of the results, the selected control signal weighting coefficient is $\lambda = 0.001$. This strategy is characterized by having the minimum use of the actuator, that is, the minimum water flow, which is approximately a 28% less than in the test with a $\lambda = 0.0001$, and the difference among the PMV index and indoor air temperature is not very significant in comparison to the other weighting coefficient.

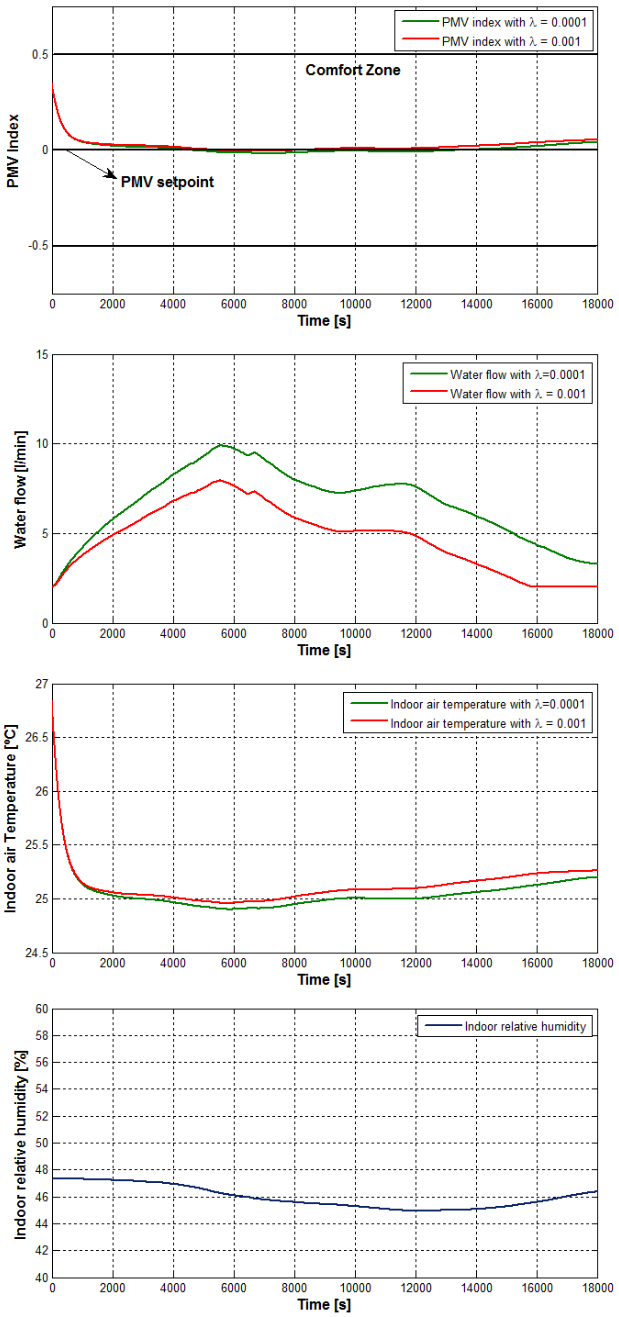

Fig. 4. Simulation results using PNMPC control strategy.

VI. CONCLUSIONS AND FUTURE WORKS

Energy saving in the use or construction of buildings is a topic that is receiving great attention by companies and from a scientific and technical point of view. After several comfort analysis inside the CDdI-CIESOL-ARFRISOL building, it has reached the conclusion that it is necessary the use of control systems in order to obtain a tradeoff between users' comfort and energy consumption of the HVAC system.

This paper is focused in the application of a practical nonlinear model predictive control approach inside the CDdI-CIESOL-ARFRISOL building, PNMPC, using only a cost function, that involves thermal comfort and the use of the HVAC systems, and a nonlinear model based on first principles that represents the thermal behaviour of the building. This strategy has been tested in simulation inside one of the more characteristic rooms of the building. The results, have determined that this control approach is able to maintain thermal comfort inside a comfort zone minimizing the use of the HVAC system.

In future works, real tests with this approach will be realized inside the CDdI-CIESOL-ARFRISOL building. Finally, the results of this approach will be integrated into a MIMO system, which allows to control thermal comfort and indoor air quality inside a characteristic room, using for that, the HVAC system, natural ventilation through the window, and blinds.

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REFERENCES

[1] P. D. Morosan, R. Bourdais, D. Dumur, and J. Buisson, "Building temperature regulation using a distributed model predictive control," *Energy and Buildings*, vol. 42, pp. 1445–1452, 2010.

[2] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy and Buildings*, vol. 40, pp. 394–398, 2008.

[3] I. H. Yang, M. S. Yeo, and K. W. Kim, "Application of artificial neural network to predict the optimal start time for heating system in building," *Energy Conversion and Management*, vol. 44, pp. 2791–2809, 2003.

[4] D. Kolokotsa, D. Tsiavos, G. S. Stavrakakis, K. Kalaitzakis, and E. Antonidakis, "Advanced fuzzy logic controllers design and evaluation for buildings' occupants thermal - visual comfort and indoor air quality satisfaction," *Energy and Buildings*, vol. 33, pp. 531–543, 2000.

[5] F. Nicol and M. Humphreys, "Adaptive thermal comfort and sustainable thermal standards for buildings," *Energy and Buildings*, vol. 34, pp. 563–572, 2002.

[6] M. Castilla, J. D. Álvarez, M. Berenguel, M. Pérez, J. L. Guzmán, and F. Rodríguez, "Análisis de confort térmico y consignas para control en el edificio bioclimático CIESOL," in *XXX Jornadas de Automática, Valladolid (in Spanish), España*, 2009.

[7] M. Castilla, J. D. Álvarez, M. Berenguel, M. Pérez, F. Rodríguez, and J. L. Guzmán, "Técnicas de control del confort en edificios," *Revista Iberoamericana de Automática e Informática Industrial (in Spanish)*, vol. 7, no. 3, pp. 5–24, July 2010.

[8] E. Camacho and C. Bordons, *Model Predictive Control*. Springer, 2004.

[9] A. Plucenio, "Desenvolvimiento de técnicas de controle não linear para elevão de fluidos multifásicos," Ph.D. dissertation, Universidade Federal de Santa Catarina, 2010.

[10] J. A. Ferre, M. Pasamontes, M. Castilla, M. J. Jiménez, and M. Pérez, "Diseño, implementación y explotación de un sistema de adquisición de datos en el edificio bioclimático CIESOL en la Universidad de Almería)," in *XXX Jornadas de Automática, Valladolid (in Spanish), España*, 2009.

[11] M. Pasamontes, J. D. Álvarez, J. L. Guzmán, and M. Berenguel, "Hybrid modeling of a solar cooling system," in *IFAC International Conference on Analysis and Design of Hybrid System, ADHS09. Zaragoza, Spain*, September 2009.

[12] ISO7730, *Moderate thermal environment.- Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*. International Organisation for Standardisation, 1994.

[13] ASHRAE55, "Thermal environment conditions for human occupancy," *American Society of Heating, Ventilating and Air Conditioning Engineers*, 1992.

[14] P. O. Fanger, "Assessment of man's thermal comfort in practice," *British Journal of Industrial Medicine*, vol. 30, pp. 313–324, 1973.

[15] Ashrae, *ASHRAE Handbook - Fundamentals*. Refrigerating American Society of Heating and Air-Conditioning Engineers, 2005.

[16] M. Sherman, "A simplified model of thermal comfort," *Energy and Buildings*, vol. 8, pp. 37–50, 1985.

[17] R. de Dear and G. S. Brager, "The adaptive model of thermal comfort and energy conservation in the built environment," *International Journal of Biometeorology*, vol. 45, pp. 100–108, 2001.

[18] J. Hoof, "Forty years of Fanger's model of thermal comfort: comfort for all?" *Indoor Air*, vol. 18, pp. 182–201, 2008.

[19] J. A. Orosa, "Research on general thermal comfort models," *European Journal of Scientific Research*, vol. 2, pp. 217–227, 2009.

[20] J. W. Wan, K. Yang, W. J. Zhang, and J. L. Zhang, "A new method of determination of indoor temperature and relative humidity with consideration of human thermal comfort," *Building and Environment*, vol. 44, pp. 411–417, 2009.

[21] IDAE, *Regulation of heating in buildings (in Spanish. Reglamento de instalaciones térmicas en los edificios). Technical Report*. Ministerio de Industria, Turismo y Comercio de España, 2007.

[22] M. Castilla, J. D. Álvarez, M. Berenguel, M. Pérez, J. L. Guzmán, and F. Rodríguez, "Comfort optimization in a solar energy research center," in *Proceedings of the IFAC Conference on Control Methodologies and Technology for Energy Efficiency, Vilamoura, Portugal*, March 2010.

[23] J. Liang and R. Du, "Thermal comfort control based on neural network for HVAC application," in *Proceedings of the 2005 IEEE Conference on Control Applications, Toronto, Canada*, August 2005.

[24] M. Castilla, J. D. Álvarez, M. Berenguel, F. Rodríguez, J. L. Guzmán, and M. Pérez, "A comparison of thermal comfort predictive control strategies," *Energy and Buildings*, no. 43, pp. 2737–2746, 2011.