THERMAL CONTROL STRATEGIES APPLIED IN BUILDINGS WITH INTERMITTENT HEATING

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This paper presents control strategies applied in buildings with intermittent heating that have as purpose the optimization of energy consumption of buildings. In this paper a brief overview of methods of thermal control that are currently applied on buildings and drawbacks of each of these methods is presented.

The study is continued with the presentation of an advanced control strategy that tries to solve the issues of other control strategies and highlights the personal contributions. The strategy employed is based on predictive control and tries to fulfill the main objective of heating control by using weather forecasts and program occupancy of buildings.

Keywords: control strategy, process, thermal control, predictive control, energy efficiency, thermal comfort, energy consumption, intermittently heating

1. Introduction

Global warming and natural resources depletion are some of the biggest threats for the near future. These two problems are treated with the utmost importance by the members of the scientific community. To support them and to minimize the effects of these issues, several decisions have been taken, for example, the European Union proposed to reduce by 20% the greenhouse emissions and energy efficiency to increase by the same percentage by 2020. Less developed member countries have taken the decision to renovate the existing buildings in order to achieve those objectives. On the contrary, the developed countries have decided to build new energy efficient buildings or even energetic independent buildings and with near-zero emissions. However, goals can only be achieved by the optimization of energy consumption, especially for existing buildings [1].

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The forecasts and the proposals from the above are based on the fact that the residential sector of the member states is responsible for about 40% of total energy consumption and about 35% of gaze emissions with greenhouse effect. The heating systems of buildings consume about 50% of energy, which represents over 20% of total energy consumption [2]. In this context, nowadays there is a growing need for the optimization of the energy consumption and to develop advanced strategies of thermal control that can be applied to buildings. One possible solution may be the idea proposed in this paper.

Several studies on the optimization of energy consumption of buildings have been made lately both in simulated environment and with directly applied on buildings [3, 4]. Even if these studies’ goal was to obtain the optimization of energy efficiency of the heating systems, the most widely used control strategies currently applied in all the buildings are based on PID controllers [5, 6]. This strategy has a series of issues that will be discussed in section 2. It is known that the first phase in obtaining building thermal control is to take into consideration the large inertia of these systems. Thus, the benchmark is not the only issue of thermal control. In order to apply an appropriate strategy, many factors need to be taken into account. Several studies have shown that if the future occupancy program of the building and the weather forecast are used, significant improvements in terms of comfort and energy consumption are brought [3, 6, 7, 8, 9].

Heating of buildings after an intermittent operation program began to be widely used because of the benefits in terms of energy savings. This operation is possible because the employment program may be known in advance for any building. By using an appropriate control strategy, this approach leads to the main goal of building thermal control: thermal comfort with minimum energy consumption. Yet there are a lot of questions, including the period for which the comfort should be provide, the regression time during the early period of occupation and how they can be rejected certain perturbations that occur in the process. The solution presented in this paper tries to answer to some of these questions.

In buildings heated by an intermittent program, load calculation is very important and this can be seen as an issue of control. When changing the heating program, the calculation way of indoor temperature regression time plays a major role, time that has a great influence on peak load and implicitly on energy consumption. If setback time is small, the peak load will have a great value, but the power consumption is reduced [10].

In order to solve the issue mentioned in the above, in section 3 of the paper, thermal control strategy based on predictive control (MPC - Model Predictive Control) will be presented. By applying these control strategies requires firstly the existence of a dynamic model of the building in which it is applied. The solution proposed here uses the program occupancy of the building which is implemented in cost function calculation, thus the main objective of thermal control is provided. The insurance of the thermal control will be demonstrated in Section 4 where by taking into consideration the model, occupancy program and weather forecast, we will demonstrate that the proposed strategy meets the primary objective of building thermal control (the comfort with minimal energy consumption).

2. Thermal control strategies used nowadays

In the next section, we will compare briefly the most important strategies of thermal control applied in buildings.

The simplest thermal strategy of the buildings is the room temperature control via on-off principle. This strategy implies that the heating devices in the room should be switched on and off depending on a certain error value of the room temperature ($e_\theta = \theta_{set\text{-}point} - \theta_{room}$), usually implemented as an appropriate hysteresis curves $C_{on\text{-}off}$:

$$G = C_{on-off}(e_\theta) \tag{1}$$

This type of control gives feedback and is the simplest control strategy. The problem is that system dynamics is not taken into consideration by the control strategy.

Another control strategy is represented by the weather-compensated control, which is actually a feedforward control. As the previous case, this strategy does not contain any information about the system dynamics. Heating medium, represented by water (θ_{water}) has set the temperature depending on the outside temperature $\theta_{outside}$ through a predetermined heating curve $G_{w\text{-}c}$:

$$\theta_{water} = G_{w-c}(\theta_{outside}) \tag{2}$$

From previous studies on thermal control strategies of buildings, radiators are fitted with thermostatic valves heads in most buildings with hydronic heating systems. Regarding the energy savings achieved, the results are not very good due to the users' inexperience that does not use them according to technical-constructive characteristics. The main negative effect produced by misuse is room's overheating. In order to solve the problem, these valves are equipped with the PID - Fig. 1.

The control strategy based on PID controller use is the most employed strategy of thermal control of buildings. This is also a type of feedback command, but unlike the other two strategies presented, this contains some information about the system dynamics (heating water temperature θ_{water} is determined by the room temperature error e_θ and a certain history – *history*) :

$$\theta_{water} = f_{PID}(e_{\theta}, history) \quad (3)$$

Fig. 1. Valve equipped with PID controllers in a building in Romania

In most cases, these controllers are not designed specifically in order to reduce the energy consumption, and the feedback loops introduce a gap between the room temperature and the reference point, whether we are talking about radiator heating systems or electric heaters - Fig. 2. In this way, the comfort is adversely affected [5, 6].

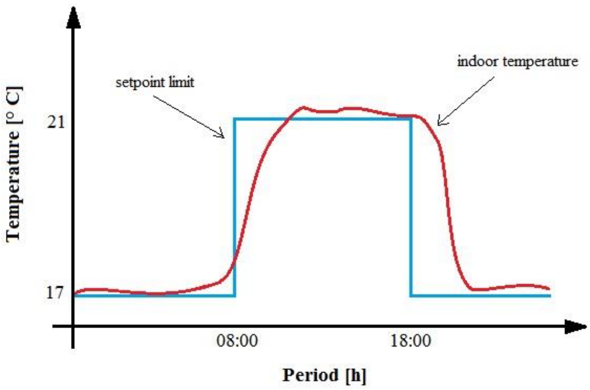

Fig. 2. Gap between the room indoor temperature and benchmarks

To compensate the fact that the building dynamics is rather slow (the building has a high inertia), there is a possibility that the process of heating starts in advance, so that at the beginning of occupancy period, the temperature does not remain under the comfort zone. PID controllers used in this strategy have as main objective to track the reference value. The problem of this control strategy is the variation of meteorological factor that is not taken into account and perturbs the system. Even if the warming up starts in advance at the beginning of the occupancy period, the temperature will follow the set reference point, it is not guaranteed that it will be in the optimal start control area, as you can see in Fig.3. Basically, the optimal starting system is not guaranteed when the strategy of thermal control based on PID controllers is used, and when it is possible, the quantity of consumed energy is very high.

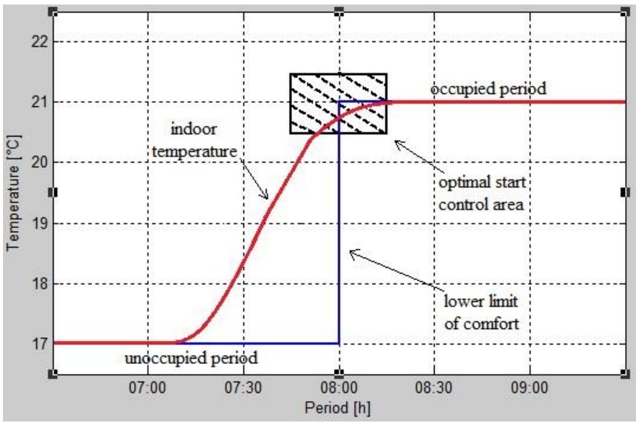

Fig. 3. Optimal starting system

Starting optimal systems of heating is covered by EN 12098-2 European standard [11]. Conforming to the norm, optimal start warming is achieved if the graph of interior temperature intersects the area of optimum starting control, as you can see in Fig. 3. This control area is set so that when the employment program changes, the temperature can vary within a maximum of 1 °C (±0.5 °C compared to the lower limit of comfort), for maximum 30 minutes (±15 minutes compared to the time change of the occupancy program). Another method that can be used to determine if inside thermal comfort is provided is the calculation of Predictive Mean Vote (PMV) and Predicted Percentage of Dissatisfied People (PPD) indices [12, 13]. We believe that the use of the method stipulated in EN 12098-2 European standard allows us to easily demonstrate that the internal thermal comfort is assured with minimum energy consumption.

3. Thermal control strategy based on predictive control

In order to meet current requirements for thermal control of building, the simple rejection of disturbances and temperature stabilization is not a satisfactory solution. Additional objectives of the regulation process refer to comfort insurance and to minimize the energy consumption. To achieve these objectives and solve the problems related to the control strategies presented in the previous section, we propose below a new strategy of thermal control.

The regulation issue becomes more difficult to implement when we want to achieve the control for multiple-input multiple-output systems (MIMO). For these systems we need to consider another control strategy that uses more possible variables (the outside temperature $\theta_{outside}$, the weather forecast $\theta_{predicted}$, and other information *x*) and the system dynamics (*history*) must be also included:

$$t_{water} = f_{MPC}(e_{\theta}, t_{outside}, t_{predicted}, x, history) \quad (4)$$

The best solution to apply this control strategy for MIMO systems (which are typical for heating systems) represents the use of Model Predictive Control (MPC). MPC allows the insurance of indoor comfort with minimal energy consumption by using a dynamic model, the occupancy program of the building and weather forecast. This method has been successfully used in other research domains [14, 15], but recently a deep interest has been shown in research of thermal control of buildings [4, 6, 7]. The main difficulties of the application of this strategy are the high demands for used computing resources and the very strong mathematical background that is used, especially regarding the controller modeling.

In the strategy of thermal control, the comfort-related requirement is imposed by an interval of temperature (defined by an upper and lower limit). The indoor temperature should be within this interval which needs to be different for the occupied period and unoccupied period. The house that has been used in this experiment is equipped with electric heating systems. Therefore, by considering a reference interval of temperature for the unoccupied period, we can observe inefficiency in terms of energy consumption. On the other hand, this solution is appropriate only for hydraulic heating systems. In these cases, transition time reduction is the main goal by keeping the temperature in this defined interval between the two occupied- unoccupied periods.

In order to solve the problem of thermal control using MPC, it is necessary to change the minimization criterion of this strategy accordingly to the future occupancy program of the building. This procedure ensures the comfort from the beginning of the occupied period without the need to ensure comfort during the unoccupied period. Thus, the criterion of energy consumption is maximum minimized. MPC can be used to predict the behavior of the building for a specific time horizon unless there is a process (building) model. For a building seen as a single thermal zone, linear representation in discrete time of the system has the following ARX form:

$$Q(z^{-1}) \cdot y(k) = W(z^{-1}) \cdot u(k-1) + P(k) \quad (5)$$

, where $u(k)$ is the system input (heating power), $y(k)$ is the system output (the indoor air temperature), $P(k)$ is the system perturbation, z^{-1} is a delay operator, and $Q(z^{-1})$ and $W(z^{-1})$ are two polynomials defined as:

$$\begin{cases} Q(z^{-1}) = 1 + q_1 \cdot z^{-1} + q_2 \cdot z^{-2} + ... + q_n \cdot z^{-n} \\ W(z^{-1}) = w_0 + w_1 \cdot z^{-1} + w_2 \cdot z^{-2} + ... + w_n \cdot z^{-n} \end{cases} \tag{6}$$

Using this control strategy, the command sequence is obtained by minimizing a cost function. In the predictive control, the most common form of the cost function is:

$$J(k) = \sum_{i=N_1}^{N_y} \delta(i)[\hat{y}(k+i) - y^{\theta}(k+i)]^2 + \sum_{i=0}^{N_u-1} \lambda(i)[u(k+i) - u(k+i+1)]^2 \tag{7}$$

, which can be written in minimized for as:

$$J(k) = \sum_{i=N_1}^{N_y} \delta(i)[\hat{y}(k+i) - y^{\theta}(k+i)]^2 + \lambda \sum_{i=0}^{N_u-1} \Delta u^2(k+i) \tag{8}$$

This optimization criterion has two terms: one that refers to the error and one that refers to the control effort. Depending on the cost, the minimum and the maximum value of the prediction horizon is represented by N_1, and N_y, the predicted output is $\hat{y}(k+i)$, and the future reference value is $y^{\theta}(k+i)$. Weighting coefficient for error is δ, and the weighting coefficient for command is λ. N_u is the control horizon and Δ_u is the command increment. The way of future outputs can be calculated in matrix form, predicted for the time horizon N_y and it is defined by the following formula:

$$\hat{y} = Fx(k) + \psi_1 u + \psi_2 p \tag{9}$$

,where matrices F, ψ_1 and ψ_2 are functions of the model with constant parameters that are not necessary to be calculated during the control.

In order to solve the delay problem presented in the section related to the control strategy that uses PID controllers, the following cost function is proposed. This cost function is built on the above function. Furthermore, the cost function integrates the future occupancy program, as an error weight term:

$$J(k) = \sum_{i=N_1}^{N_y} \delta^k(i)[\hat{y}(k+i) - y^{\theta}(k+i)]^2 + \lambda \sum_{i=0}^{N_y-N_1} u(k+i) \tag{10}$$

, with the following conditions:

$$\begin{aligned} 0 \le u(k+i) \le P_{max}, \quad & \forall\, i = 0 \ldots N_y - N_1 \\ u(k+i) = u(k+N_u-1), \quad & \forall\, i = N_u \ldots N_y - N_1 \end{aligned} \tag{11}$$

In this example, the error weight term $\delta^k(i)$ is the future occupancy program defined as:

$$\delta^k(i) = \begin{cases} 1, & \text{if } k+i \text{ corresponds to the occupied period} \\ 0, & \text{if } k+i \text{ corresponds to the unoccupied period} \end{cases} \tag{12}$$

Since our objective is to minimize the energy consumption, the term related to control effort in the cost function was changed in u and quadratic form was eliminated.

Fig. 4 shows the changing way of $\delta^k(i)$ factor from 0 values to 1 and vice versa. The existence of this factor in the cost function allows the absence of a reference point in the unoccupied period. Thus, in this period only the issue of the efficiency of energy consumption should be observed. However, if a person enters the building during the unoccupied period and the conditions of comfort are not ensured, the weighting coefficient for error, δ, has to be changed so that all its elements become 1.

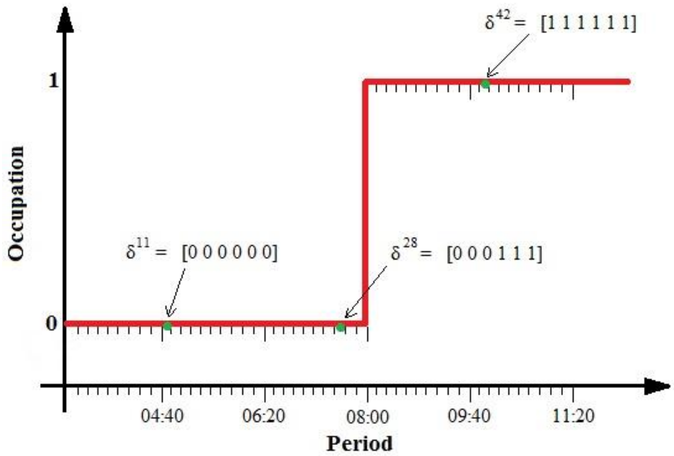

Fig. 4. Change of weight factor value, $\delta^k(i)$

When it is strictly necessary for the minimization of computational demand and very low temperatures avoidance during the unoccupied period, a minimum temperature value can be imposed:

$$\hat{y}(k+i) \ge T_{min}, \quad \forall i = N_1 \ldots N_y \tag{13}$$

4. The results of the experimental test

In order to realize experimental tests that can prove the solution presented in the above, solution that improves the employed strategy of control, the used data has been collected from sensors fitted in an experimental house with an area of 100 m^2, located in southern Germany [16]. The collected data are indicators on the indoor and outdoor environment (indoor temperature, solar irradiance flux, etc.), and the outdoor temperature measured via weather stations. These data correspond to the period 09.04.2014 - 28.04.2014, and have a sampling period of 10 minutes. The indicators evolution is graphically represented in Fig. 5.

In our experiments, we considered the house as a multiple inputs single output (MISO) system that can be represented by a block diagram with 4 inputs and one output - Fig. 6. Outdoor air temperature, supply air temperature, solar radiation incident on the envelope of the building and heat flux density are considered the system inputs and the indoor temperature is considered the system output.

The mathematical model for the presented home, necessary to implement this control strategy, was obtained by us in [17] and the response of the system can be seen in graphical form in Fig. 7

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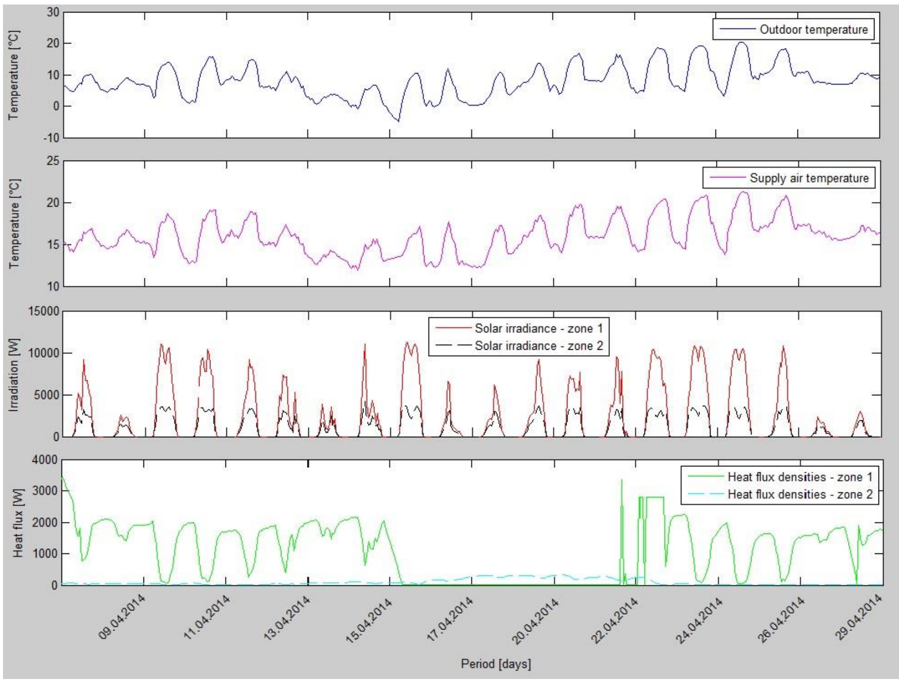

Fig. 5. Measured data (outdoor temperature, supply air temperature, solar irradiance, heat flux densities)

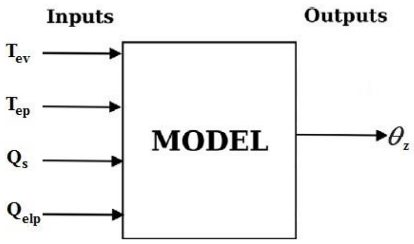

Fig. 6. The block diagram of the MISO system

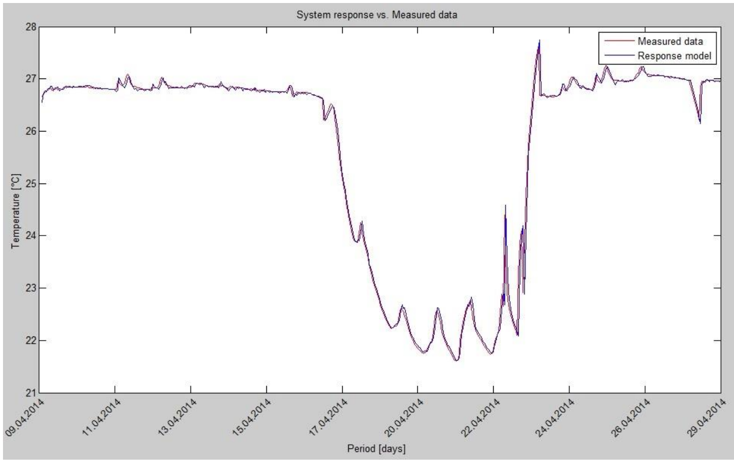

Fig. 7. Comparison between measured data and model response

Using the mathematical model of the house, the occupancy program presented in Table 1 and the data on weather forecast, we obtained the minimum value for the cost function presented in the section 3.

Table 1

Occupancy program of the house

Period type	Daily program	Setpoint
Occupied period	8:00 – 20:00	22.5 °C
Unoccupied period	20:00 – 8:00	21 °C

By implementing the function in Matlab program, we obtained the system response by using this strategy of thermal control for one of the monitored days. In order to observe the improvements brought by this control strategy, the obtained response is compared with the one of an implemented strategy that uses PID controllers for thermal control. The comparison of these results can be seen in graphical form in Fig. 8.

As we can see, the proposed control strategy is the recommended solution for thermal control of the building. The proposed strategy provides an optimum control of the temperature because at the beginning of the occupancy program, the optimal is assured (heating is on in advance to fit the optimal starting area specified in Section 2), and during the occupancy program.

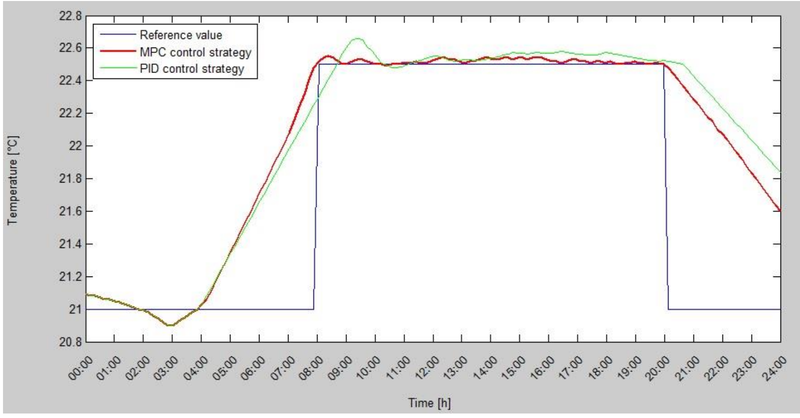

Fig. 8. Comparison between MPC and PID control strategy

Unlike the solution of PID controller, the energy consumption is smaller, the building overheating is avoid, the heating system is controlled in correlation with the occupancy program of the building, this is how a high level of comfort is provided.

5. Conclusions

The control strategy presented in this paper employs occupancy program of the building and implements it in calculating the cost function as an error weight. The result of this implementation of control strategy has been compared to the result for the same building, but controlled with PID controllers. Tests results have shown that using the presented strategy, energy consumption is reduced and comfort is improved. In this way the main objective of thermal control is fulfilled. We found out that if the occupancy program exists in the cost function, the control strategy can start heating in advance and at the beginning of occupancy, the comfort is assured. One the other hand, that strategy that PID controllers, the comfort of the beginning occupancy period can be ensured only with a higher energy consumption.

In order to improve the results, as future perspective, we wish to realize an algorithm that can be used to describe how the strategy presented is applied using MPC control method.

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