Advanced Control for Intermittent heating

Stéphane DUBURCQ[*] **- Sylvain GUILLERMINET**[**]

Keywords : adaptive control, predictive control, intermittent heating, robustness, model

Summary :

For the heating of buildings occupied on a discontinuous basis, intermittent heating control devices are used. This article presents one which incorporates advanced automatic control techniques (predictive temperature control and adaptation of the internal model). The results obtained are compared with those achieved using standard control devices. They are validated on the installation used to determine the initial settings and on slightly different installations in order to compare their robustness with respect to the various characteristics of the heating loop and of the building.

Introduction

For reasons based essentially on the need to conserve energy, French legislation requires that specific "intermittent" heating systems be used in buildings occupied on a discontinuous basis (offices, schools, etc.). Intermittence is characterized by four modes of operation :

- an off mode (mode 0) or low-output mode (mode 1) during unoccupied periods (nights and weekends) which maintains the interior temperature above freezing point;

- a preheat mode (mode 2), lasting as short a time as possible prior to each occupied period, during which energy output is maximum in order to raise the internal temperature up to the comfort temperature before occupancy;

- a high-output mode (mode 3) during occupied periods to maintain the comfort temperature.

[*] Gaz de France / R & D Division - DéGIMA/GSA
361, avenue du Pdt Wilson - 93211 SAINT-DENIS LA PLAINE - FRANCE
email : stephane.duburcq@edfgdf.fr

[**] Altran Technologies for Gaz De France / R & D Division

The various intermittent heating systems currently available are characterized by their preheat strategy, i.e., the method used to calculate when to switch over to preheat mode (mode 2) and, to a lesser extent, by the type of control used outside the preheat period (modes 1 and 3), a factor which is not specific to intermittent heating but which may be important in economic terms.

Intermittent control devices must satisfy ever more demanding requirements, in terms not only of comfort (accurate temperature control) but also of energy consumption and loads on the installation.

The aim of simulation work performed by the Gaz de France R & D Division was to develop a control device using advanced automatic control techniques and to compare it with standard ones, first on a nominal system and then on slightly different systems in order to determine its robustness.

After a presentation of the installation (heating loop and building), the control devices which served as a basis for comparison of results are described. The operation of the predictive-adaptive control device developed by us is then detailed. Lastly, we examine their robustness with respect to the heat production system and the building. Various factors are successively modified to see if the adaptive-predictive controller (set for a nominal installation) is able to deal with these erroneous parameters.

The installation

The complete system comprises a building, a heating loop, an intermittent heating system and a controller. The system was modelled under ALLAN.Simulation ([1] and [2]).

The heating loop essentially comprises :

- a primary heat production loop. This includes a condensing boiler, which takes priority, and a conventional boiler mounted in parallel and controlled by aquastats, with an expansion vessel to balance water pressure in the system, two pumps and pipes connecting the various components to each other;

- a secondary heat distribution loop. This includes a three-way valve to mix the water from the primary and secondary circuits, radiators to heat the building, the condensing boiler condenser, one pump and pipes connecting these components to each other. The radiators are not fitted with thermostatic valves.

Ventilation is provided by a fixed system operating at a rate of 0.62 vol/h during occupied periods and 0.15 vol/h during unoccupied periods.

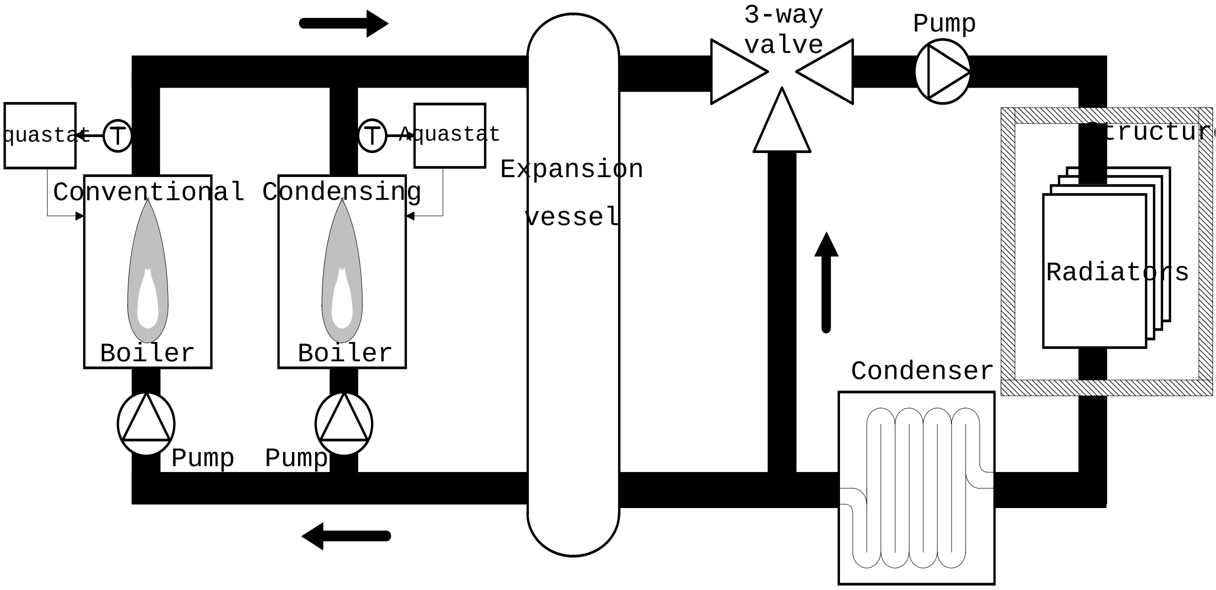


Figure 1 : Diagram of the heating loop

The building under study is a single-zone commercial building with a volume of 5560 m^3. Apart from the space heating system, only the influence of outside temperature is taken into account, with other internal and external heat inputs being ignored* . The building is occupied from Monday to Friday from 8h to 19h.

The building model used for this study is a linear second-order model taking into account two time constants. The internal temperature taken into account and used as a variable to be controlled is, in our case, the building temperature. In the case of a more complex building comprising several zones, the temperature judged to be most representative (often in the coldest zone) would be controlled in the same way.

We chose the air temperature rather than return water temperature since air temperature directly affects the comfort of occupants. Moreover, by controlling this quantity directly in a closed loop, the control system is less sensitive to disturbances.

A number of operating constraints must be respected by the real system and are taken into account in simulation :

- internal temperature maintained above 12°C during unoccupied periods;

- internal comfort temperature maintained at 19°C during occupied periods.

Presentation of reference control devices

Two reference control devices were used. They correspond firstly to the legal minimum imposed since 1987 and secondly to a widely used type of control device which will doubtless

* We subsequently confirmed that these heat inputs did not modify the behaviour of the different control devices

become obligatory in the near future. Hereafter, they will be referred to respectively as control devices N2 and N4.

The N2 control device

This type of control device represents the legal minimum imposed by legislation covering commercial premises which came into force in 1987. The following heating modes are triggered at preset hours :

- normal heating with temperature control by linear water temperature control law during occupied periods;
- total heating shutdown at the end of the occupied period;
- preheat at full output during a preheat period of fixed duration.

The control device also turns on the heating system at normal output during unoccupied periods if the internal temperature falls below a minimum threshold level (12°C).

The N4 control device

The N4 control device architecture is similar to that of the N2 one, except as regards the triggering of building preheating, since with the N4, the preheat period is calculated and not preset. The length of the preheat period depends on the external temperature and on the internal temperature of the zone concerned.

The moment when preheating is triggered corresponds to the moment when the internal temperature curve crosses the "decision line". This line is calculated by linear extrapolation according to the mean internal and external temperatures.

The control device was adjusted in accordance with the recommended state of the art: we simulated an external temperature of -7 °C and adjusted the control device to ensure that the comfort temperature has always been reached by the beginning of the occupied period.

During unoccupied periods, when the internal temperature falls below the minimum threshold level, the heating system comes into operation at low output.

When, during the preheat phase, the internal temperature rises above a certain set level, space heating comes under the control of the central control system.

The predictive and adaptive control device

This type of control device [3] contains a more sophisticated automatic control system than the ones traditionally used for building heating. It controls the internal temperature directly in a closed loop, not simply the temperature of the water leaving the boiler. This predictive functional control (PFC) [4] acts on two levels : it predicts the instant when the heating system should be turned on and controls the temperature during occupied and unoccupied periods (modes 1 and 3).

Predictive control

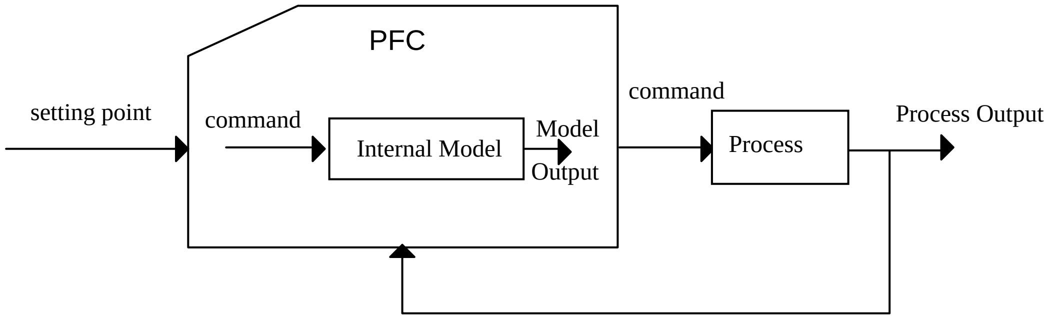


Figure 2 : principle of PFC control

The PFC control technique involves the use of an "internal" model built into the calculator. At each calculation step, control decisions are calculated as a function of a path converging towards the set level and a prediction of the future behaviour of the process.

A PFC controller may also take into account a measured disturbance in order to counteract its variations.

In our case, the process output is the internal temperature and the command is the temperature gain in the radiator. It is adjusted by means of the 3-way valve. The measured disturbance is the external temperature.

As internal and disturbance models, first order transfer functions are used. We have :

- for the internal model Mi : TRU(p) = $\frac{G1}{1+T1.p} * U(p)$

where U is the system command, here the temperature difference at the radiator terminals. This command is linked directly to the position of the 3-way valve,

G1 and T1 are the gain and the time constant of the "internal" model,

TRU is the component of internal temperature due to the command U.

- for the disturbance model Mδ : TRT(p) = $\frac{G2}{1+T2.p} * TEXT(p)$

where TEXT is the external temperature, viewed as a disturbance,

G2 and T2 are the gain and time constant of the "disturbance" model,

TRT is the component of internal temperature due to the disturbance TEXT.

We thus obtain : TRM(p) = TRU(p) + TRT(p), TRM being the modelled internal temperature.

The figure below shows the measured and modelled internal temperatures. We note that qualitative behaviour is generally well reproduced and this is sufficient for satisfactory closed loop control.

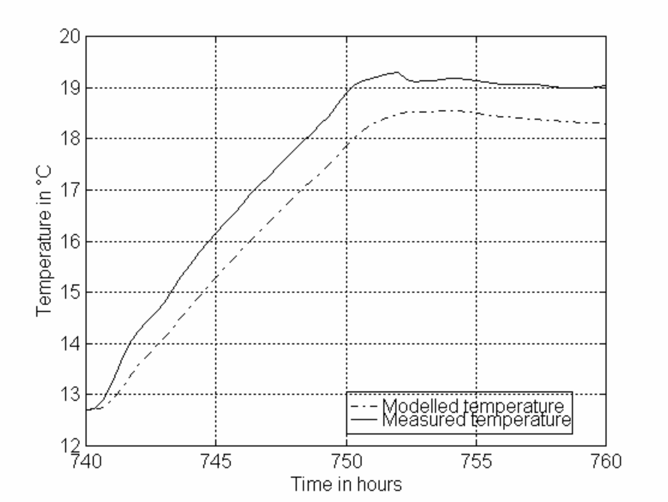


Figure 3: Comparison between measured and modelled temperatures

This type of control by internal model is intrinsically robust and can be used to offset the inaccuracies introduced by certain assumptions, such as the use of a linear internal model to represent non-linear phenomena (such as the behaviour of the 3-way valve).

Preheat phase

Using the internal model and an external temperature extrapolator, we predict the external temperature (on the basis of the external temperature during the previous 24 hours) and the behaviour of the system up to the date of the next occupied period if the heating system is turned on at full output. If the preset comfort temperature is reached before the date of occupancy, the heating is not turned on. If it is reached on the day occupancy begins, it is turned on (see figure 4).

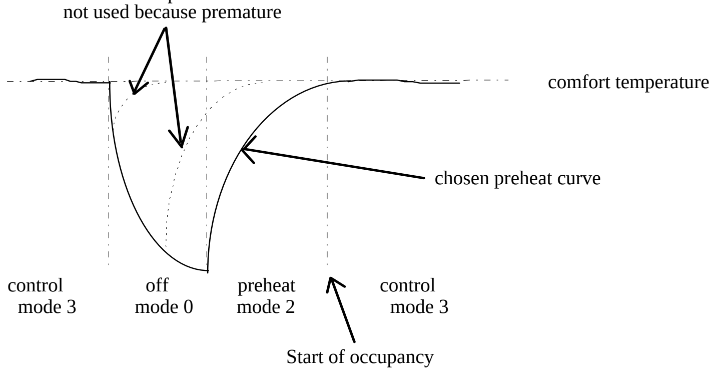


Figure 4 : calculation of optimum preheat startup time

Once the optimum moment for turning on the heating system has been determined in this way, the theoretical optimum curve is stored and becomes the reference curve to be followed by the control device. A predictive control process is triggered which will attempt to follow this curve. Hence, unlike conventional control devices, we note that the heating system will not be at full output during the preheat phase. This would be the case if the model corresponded exactly to reality.

Moreover, to ensure that the comfort criterion is satisfied, the gains of the model are deliberately under-estimated to obtain a process which is more dynamic than the model.

Adaptation of the internal model

This phase has two objectives, firstly to improve the preheat phase by refitting the internal model used to predict the behaviour of the installation, and secondly, to make the model capable of adapting to variations in building structure.

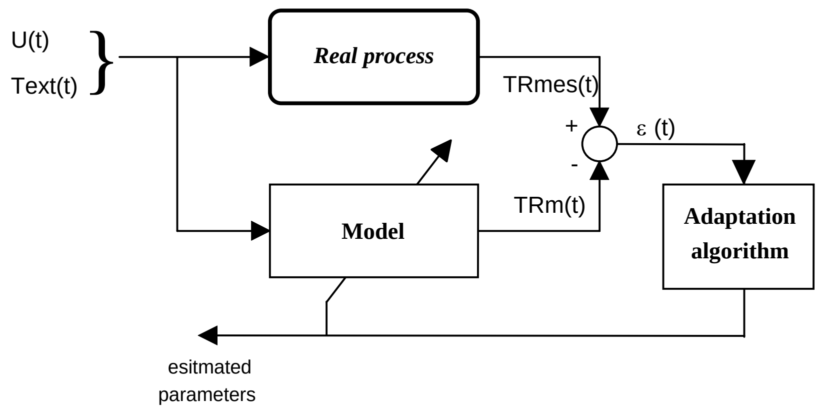


Figure 5 : Adaptation principle

On the basis of the object - model error (measured TR - model TR) and the measured inputs (the command U and external temperature), an adaptation algorithm is run to refit the model parameters : the gain G1 and the time constant T1. This adaptation is made at the end of each preheat phase and the parameters thus identified are used for the following preheat phase (see figure 6).

The parameters G2 and T2 are not adapted over time since they characterize the disturbance model. This model gives no more than a tendency compared to the internal model which gives the main component of internal temperature.

The value of these parameters is set in advance on the basis of information on a building with moderate inertia. The simulation revealed that this always results in satisfactory control.

An improved Least Squares algorithm [4] was chosen since, unlike other standard estimation algorithms, it is not biased and converges rapidly.

To make the adaptation, the model is discretized since the Least Squares algorithms work more easily with discrete models.

The internal model is a simplified representation with one gain and one time constant. However, a building is a complex structure with several time constants and its behaviour varies according to wall temperature. To take this type of phenomenon into account, especially for preheating after a weekend, two sets of parameters are used : one for weekdays and one for weekends after a longer unoccupied period. In this way, the cooling of structures can be taken into account.

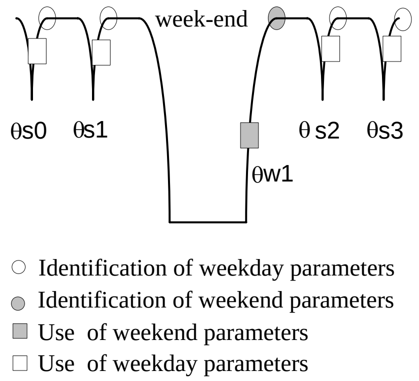
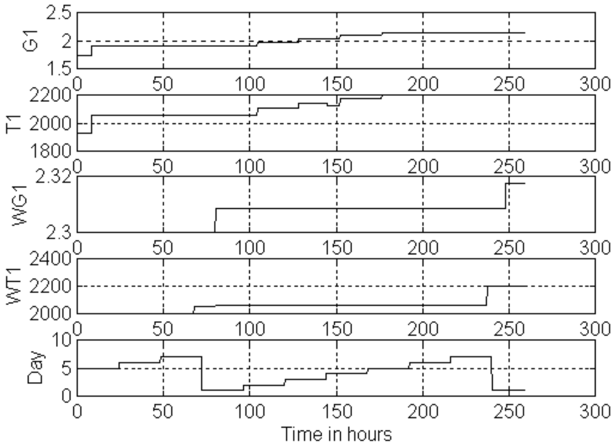


Figure 6 : Use of different parameters

If there are no modifications to the installation, the model will converge towards a solution. It is therefore necessary to define a criterion to stop the algorithm and thus avoid adaptations based solely on noise from one sensor. To this end, the gradient of each parameter is calculated and if it falls below a threshold value no adaptation is made.

However, adaptation can continue thereafter. Indeed, it may be necessary to modify the building (by adding a window for example) or the heating circuit currently in use.

The figure below illustrates the parameter variations when the control device is turned on. The gains are G1 for weekdays and WG1 for the weekend, time constants are T1 for weekdays and WT1 for the weekend.



<u>Figure 7</u> : variation in model parameters over time

We then checked that the algorithm converged, whatever the initial parameters and the external weather conditions.

This control device has being patented. Numerous control devices which calculate the moment of preheat triggering have been developed [5, 6], though they generally calculate the triggering instant according to the external temperature and the internal building temperature. There are very few which take the building structure into account [7].

Here, external temperature variations are taken into account by the "disturbance" model and an external temperature extrapolator which, on the basis of the temperature on a particular day is able to predict the external temperature during the next 24 hours.

The internal model is refitted according to the properties of the installation. This avoids the need for over-precise adjustments when the control device is first set into operation, since adjustments are refined over time to converge towards values which require no further adaptation.

Hence, when the installation control device is first used, comfort and energy performance are moderate but improve steadily over time.

Simulation tests

<u>**The nominal case**</u>

We began by comparing the adaptive PFC control device with the other ones on the nominal installation. The building has moderate inertia : the long time constant has a value of 31 hours.

The weather conditions are those of a town in the Parisian region.

Figure 8 shows that the use of closed-loop control provides better internal temperature control. Adaptation of the internal model results in improved weekend preheating.

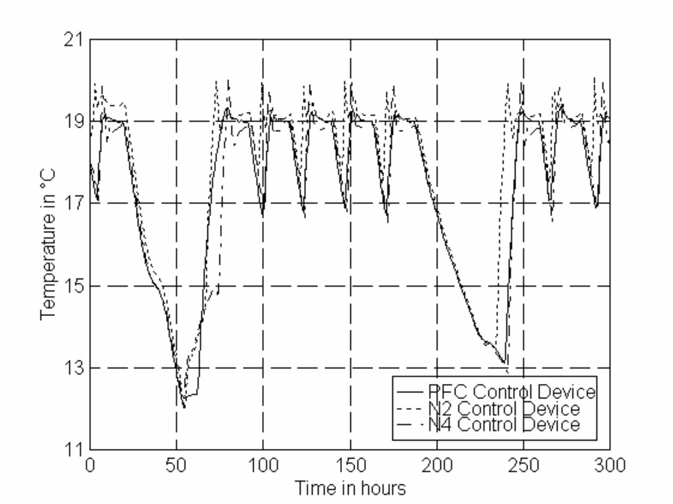


Figure 8 : Behaviour of the different control devices over 10 days

If we compare the different control devices over an entire heating season, we note that the predictive-adaptive one performs slightly better than the others in all areas (see table below) : it consumes less (between 2.5 and 5%), it exerts less load on the installation (the boilers are switched on and off less often and the total travel of the 3-way valve is half that recorded with conventional control devices).

	N2	N4	adaptive PFC
Mean difference with respect to set temperature during occupied periods (°C)	0.2	0.1	0.1
Standard deviation for temperature during occupied periods (°C)	0.14	0.20	0.11
Time during which Tint<19°C (set temperature) during occupied periods	0.4%	62%	19%
Time during which Tint<18.9°C during occupied periods	0 %	39.8%	0.9%
Standardized number of times the two boilers were switched on or off	1124	1032	1000
Standardized operating time of the two boilers	1050	1045	1000
Standardized total travel of the 3-way valve	2000	1845	1000

Standardized total consumption (kW.h)	1050	1025	1000

Summary table : nominal installation

Modification of installation design

We then modified the installation without changing the adjustments of the various control devices to compare their robustness. The aim was to see to whether a different installation could be obtained without changing the settings.

Since the N2 and N4 ones have identical behaviours, with an advantage for N4, only the results of the latter will be compared with the predictive-adaptive control device.

Building inertia

We modified the building containing the boiler plant by increasing its inertia : the long time constant was raised to 130 hours. We then simulated the new system with the same external conditions. We observed that only the predictive-adaptive control device respects the comfort and energy conservation requirements. Indeed, thanks to its capacity for adaptation, it is able to take into account the modification in building inertia for the preheat phase. The intrinsic robustness of predictive control guarantees accurate temperature control during occupied periods.

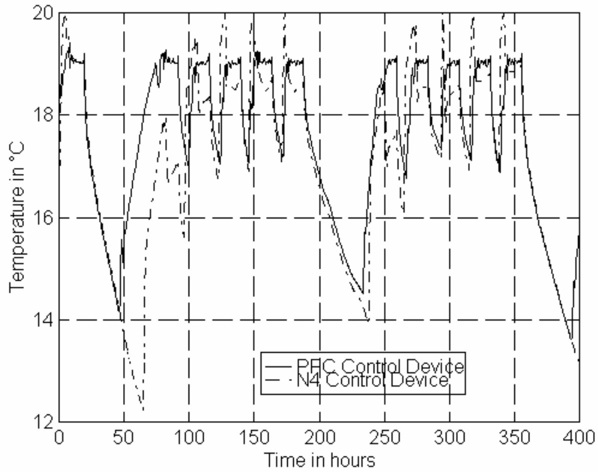


Figure 9 : High-inertia building

Modifications in the heating loop

We also sought to verify the robustness of the predictive-adaptive control device with respect to the heat production system. We therefore modified the various parameters of the heating loop while ensuring that the dimensions of the installation remained appropriate to the building. We divided the boiler output by five and reduced the building volume by five and then modified the output and surface area of radiators and losses in the circuit.

The results are comparable to those obtained when the building is modified : the predictive-adaptive control device counteracts any installation modifications during the preheat phase and, thanks to closed-loop control, is able to maintain the comfort temperature. Figure 10 illustrates the consequences of a modification in radiator surface. The N4 control device is unable to control the preheat phase adequately or to ensure that the internal comfort temperature is maintained (it rarely exceeds 18.5°C during the second week).

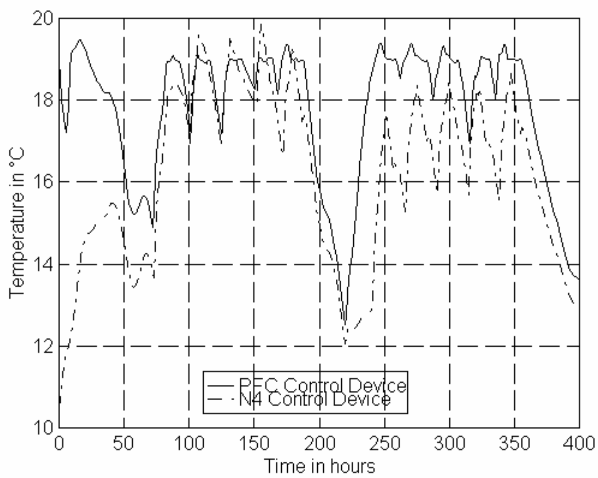


Figure 10 : Halving of radiator surface area

Simulation of a breakdown in the heating loop

The aim of the last tests was to check whether the behaviour of control devices remains consistent in the event of a breakdown or whether, on the contrary, they aggravate the consequences of this malfunction. We successively caused a breakdown in the condensing boiler and then the conventional boiler. We imagined that the 3-way valve was unable to open and close completely, that its opening and closure time was prolonged due to seizure or wear. Lastly, we simulated the existence of an offset on the temperature sensor and an increase in measurement noise.

Overall, the different control devices perform adequately in the event of a breakdown, counteracting its consequences within the limits of their capabilities. The adaptive control device reacts better to certain malfunctions since the detection of an increase or decrease in the installation response time results in an adaptation of the internal model parameters to take the event into account.

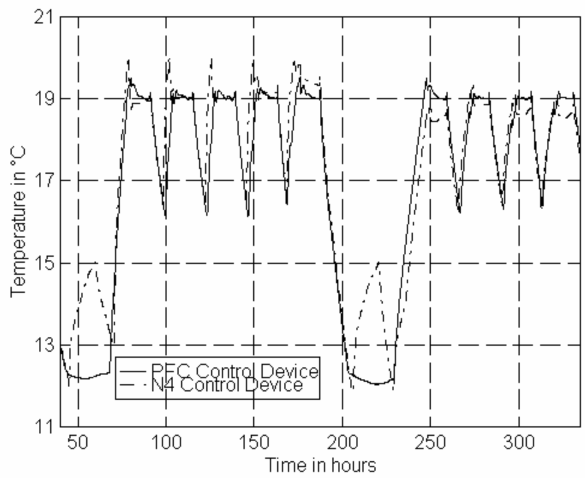


Figure 11 : Boiler breakdown at T = 200 h

For example, figure 11 illustrates the case of boiler breakdown at the end of the first week. Despite the loss of a boiler, the predictive control device ensures that the comfort temperature is maintained since the second boiler alone is capable of satisfying the building's energy needs. The N4 control device has difficulty in maintaining the comfort temperature during the day.

Conclusions

For the heating of buildings occupied on a discontinuous basis, advanced control provides a more effective solution than the intermittent heating control devices currently available. Indeed, the coupling of predictive control and adaptation of the internal model during use enhances the comfort of occupants while slightly decreasing energy consumption and reducing load on installations.

However, it is above all when conditions move away from those of a nominal installation that the advantages of this predictive-adaptive control device are confirmed. The adaptation of the internal model enables the control device to function correctly even if the building is more inert or if the heating loop is not exactly the same size. Moreover, in the event of breakdown the control device behaves satisfactorily, since it does not aggravate the consequences of equipment malfunction.

Another advantage of this control device comes to light in the installation phase : no adjustments are required when changing from one installation to another, since the adaptation of the internal model automatically adjusts the system to its new environment. Similarly, if the installation is faulty (incorrect settings for certain parameters), the control device will automatically readjust and its long-term operation will not be affected.

This control device is currently being installed for on-site validation during the 97/98 heating season.

Bibliography

[1] *”Commande prédictive d'un chauffage intermittent de bâtiments tertiaires”*, E. BOULANGER, S. ABU EL ATA, R. HALGAND, commande GDF n°X960454-689872, 1990

[2] *”Allan.™ Simulation -Release3.1 Description”*, A. JEANDEL, GDF Réf : M DéGIMA, GSA 1887

[3] *”Pratique de la Commande Prédictive”*, J. RICHALET, ADERSA, Traité des Nouvelles Technologies, série Automatique, Edition HERMES

[4] *”Identification et commande des systèmes”*, I. DORE LANDAU, Traité des Nouvelles Technologies, série Automatique, Edition HERMES

[5] *”Algorithms for Predicting recovery Time from Night Setback”*, J.E. SEEM, P.R. AMSTRONG, C.E. HANCOCK, ASHRAE Transactions 1989 V.95

[6] *”HVAC Systems Dynamics and Energy Use in Existings Buildings - Part 1”*, R.J. HACKNER, J.W. MITCHELL, W.A. BECKMAN, ASHRAE Transactions 1984 V.90

[7] *”A Robust self-tuning predictive controller for HVAC Applications”*, A.L. DEXTER, P. HAVES, ASHRAE Transactions 1989 V.95