Rule Based Control of Fan Coil Units

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Abstract

Fan coil units are widely used to realise a thermally comfortable indoor climate in rooms. The main components are the heating coil, the control valve and the fan. Hot water flows through the heating coil and heats the passing room air. In case cooling is required also a cooling coil is installed.

This paper presents a new control system. This control system uses inexpensive open/closed valves for precise control of heat, released by the fan coil unit. It uses two cascade control loops to adjust the indoor temperature. The main control loop controls the indoor air temperature. The secondary loop controls the temperature of the (supply) air leaving the unit by opening or closing the valve. The setpoint of the secondary loop is adjusted by the main control loop.

A rule based type of control for the secondary loop is presented. It is implemented in the control system of the fan coil unit and tested in a test room. Results show fast and accurate control of the supply air temperature.

This control method is also applicable for other systems that need cheaper actuators for operation as well.

1. Introduction

Consider an office room. The desired room air temperature can be realised by balancing the heat flows in the room. Heat is produced in the room by occupants, machines, artificial lightning, the sun, etc.. Heat leaves the room by thermal conductivity through walls and windows, through cracks, open windows and doors. Adding the above mentioned heat flows together results in a total 'natural' heat load $Q_{total,natural}$:

$$\dot{Q}_{occupants} + \dot{Q}_{machines} + \dot{Q}_{light} + \dot{Q}_{sun} + \dot{Q}_{transmision} + \dot{Q}_{disturbance} = \dot{Q}_{total,natural}$$

We define, that heat which is added to the room has a positive value and heat which is extracted from the room a negative value. The magnitude of the partial heat loads change with time and are not constant. Therefore the magnitude of the total 'natural' heat load will also change with time. We are not interested in the actual values of the different heat loads, but how to realise the desired room air temperature. A negative total heat load results in a reduction of the room air temperature, a positive total heat load in a higher room air temperature and a balanced total load gives a constant room air temperature. Thus the desired room air temperature can be realised by adjusting the total heat load. This can be done by adding an 'artificial' heat load to the total 'natural' heat load:

$$\dot{Q}_{total,natural} + \dot{Q}_{artificial} = \dot{Q}_{total}$$

A positive 'artificial' heat load is technically realised by means of a heating device and a negative 'artificial' heat load by means of a cooling device. The 'artificial' heat load must have the ability to change in time in order to achieve a desired total heat load, because the total 'natural' heat load changes in time as well. The heating / cooling device used here is the fan coil unit.

2. Control of a fan coil unit

Normally the positions of the valves of the heating and cooling coils are continuously adjusted by the indoor thermostat. The fan is switched to a higher speed during the preheating or precooling periods [1,2,3]. This type of control may lead to large variations in the supply air temperature. Especially during the cooling mode draught may be the result, because of the fact that too cold air will fall directly into the living zone. An improvement can be obtained when two cascade control loops are applied to control the indoor temperature as is shown in figure 1.

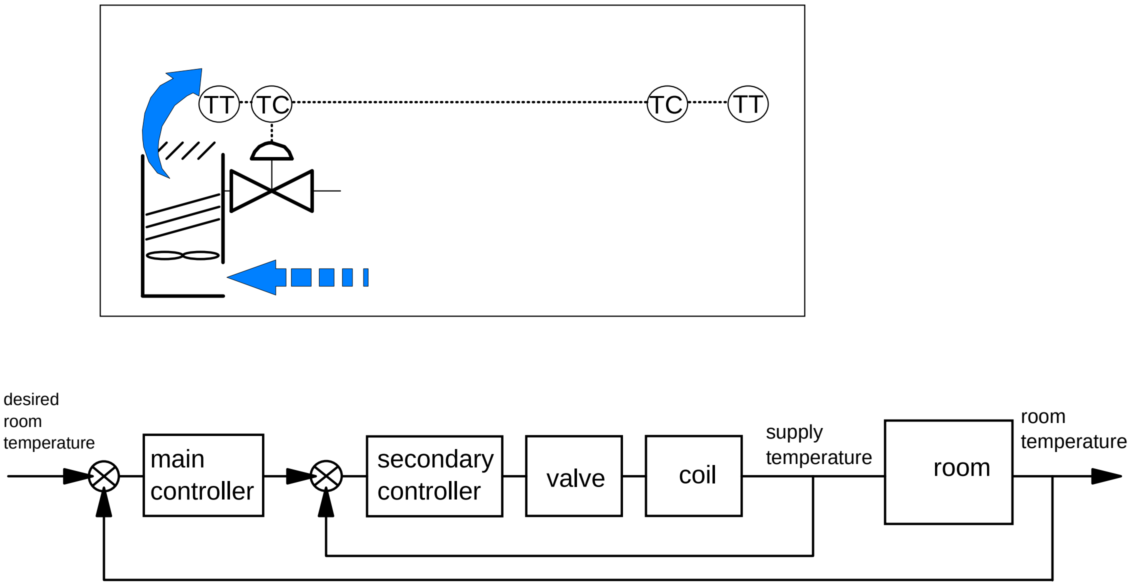


Figure 1 Control of a fan coil unit

The main control loop controls the indoor temperature by adjusting the setpoint of a secondary loop that controls the temperature of the air leaving the unit (supply air) by opening or closing one of the valves. Now overshoots or undershoots can be avoided by a proper control of the supply air temperature.

The objective of this paper is to design a better and cheaper secondary control loop. It is cheaper because of the use of on/off valves and better because of the application of a rule based control system.

3. Control of the supply temperature

The methods that will be discussed here, have one thing in common: they all use an on/off valve to control the supply temperature. The water valve has only two positions, fully opened or closed. There is no intermediate position and so the valve's characteristics are of no importance. There is only one important requirement: the elapse time from fully opened to fully closed valve or the other way around must be as short as possible. Each on/off valve will works just fine and it is much cheaper than a proportional valve.

Three methods are discussed. The first method controls the supply temperature based on the instantaneous actual measured supply temperature. This type of control is called relay control. The second and third methods are both predictive and adaptive. They control the supply temperature based on the actual measured supply temperature and the temperature measured before. These types of control are referred as PCM1, Predictive Control Mode 1, and PCM2, Predictive Control Mode 2, respectively. These control methods are implemented in the control system of a real fan coil unit and tested in a lightweight, well insulated test cell. Test results are compared.

3.1 Relay Control

The relay controller controls the supply temperature based on two settings:

1. The desired supply temperature
2. The dead band, expressed as a temperature difference

The effect of the dead band is shown in figure 2 for a heating process. The solid line indicates the actual supply temperature in time. The temperature rises when the heating valve is opened and drops when it is closed. The valve starts to close when the supply temperature passes the upper limit temperature of the dead band upwards and starts to open when the supply temperature passes the lower limit of the dead band downwards. Due to the reaction time of the valve and the thermal inertia of the heat exchanger the temperature still increases/decreases after the valve is closed/opened.

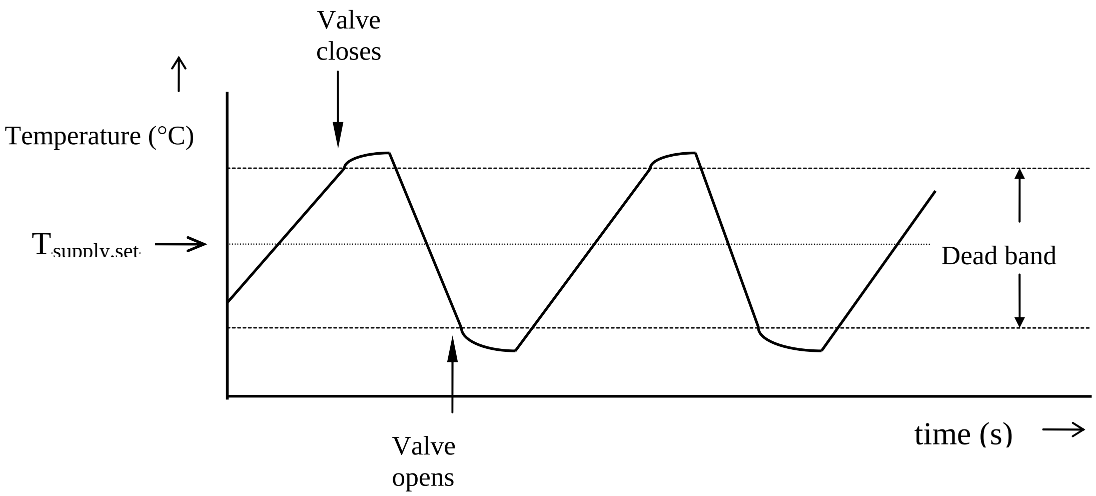


Figure 2: The Relay Controller with dead band

The elapse time between the fully opened and closed position of the valve is determined by:

1. The speed at which the supply temperature changes by the thermal inertia of the heat exchanger or by disturbances.
2. The dead band of the relay.

The setting of the dead band should assure on the one hand sufficient small temperature fluctuations and on the other hand not too short times between consecutive opening and closing of the valve.

After the relay controller was implemented in the control system of the fan coil unit in the test cell, the desired supply temperature was set at 30 °C and the dead band at 1 K. Figure 3 shows the settings and the results.
When the supply temperature drops below the lower limit of the dead band of 29.5 ^{0}C, the valve is opened. After the valve is opened the supply temperature still drops approximately 0.5 K before it starts to rise. It is closed when the supply temperature crosses the upper limit of 30.5 ^{o}C, just as expected from the desired supply temperature of 30 ^{o}C and half the dead

band of 1 K. Although the valve is closed, the supply temperature still rises approximately 7 K. It is obvious that the relay controller is not suitable to control accurately the supply temperature of the fan coil unit. A smaller dead band will have no influence on the results because the overshoots are caused by the high thermal inertia of the system.

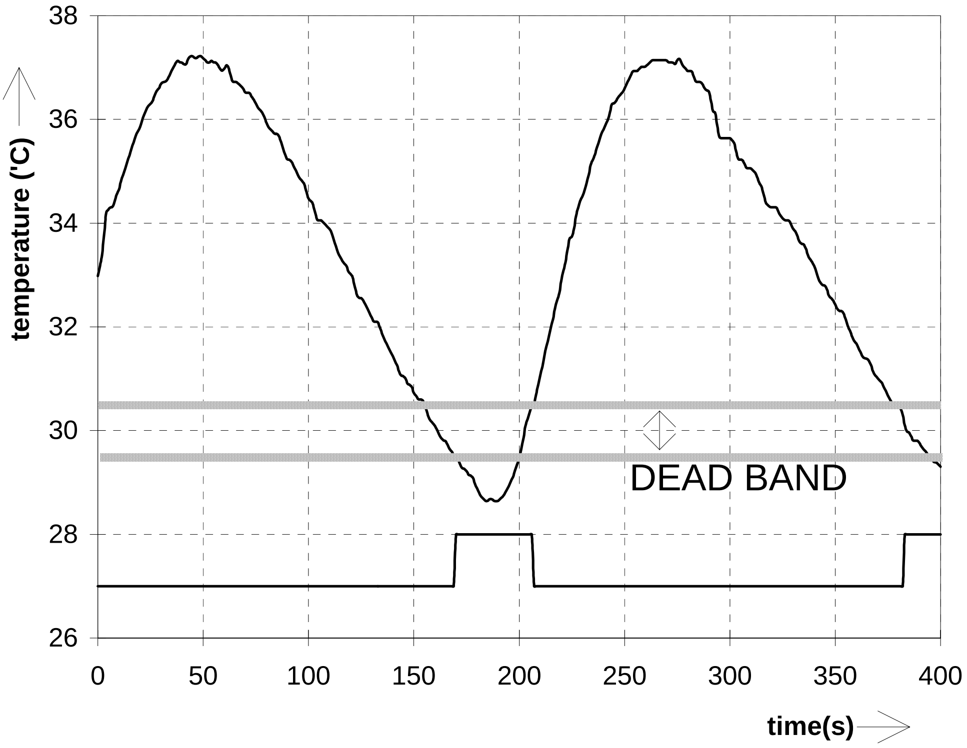


Figure 3: Test results of the relay controller

3.2 Predictive Control Mode 1 or PCM1

Actually this controller a cascade controller. The main controller is the relay controller and the secondary controller the PCM1. In the first instance only the main controller is active. As long as the relay controller offers the desired results, the PCM1 is not activated. This is the case when, for instance, the temperature of the water entering the heat exchanger does not deviate too much from the desired supply temperature. An other reason, not to activate the PCM1 at start up, is the fact, that the PCM1 requires historical data of the system behaviour in order to control it. It is obvious that it is not possible to start with the PCM1 controller for this reason. The relay controller is an easy and satisfactory method to generate past system behaviour as is needed by the PCM1.

The PCM1 controls the supply temperature based on three settings:

1. The desired supply temperature
2. The desired/allowed amount of overshoot
3. The desired/allowed amount of undershoot

The PCM1 tries to achieve these desired values using the following information:

1. The current valve’s position
2. The current measured supply temperature
3. The last overshoot of the measured supply temperature
4. Is this increased/decreased as compared to the previous one?
5. The last undershoot of the measured supply temperature
6. Is this increased/decreased as compared to the previous one?

The PCM1 is designed to reduce overshoots as well as undershoots in the supply temperature. The procedure to reduce the overshoots is the same as for the undershoots. The following explanation on reducing the overshoot will therefore suffice.

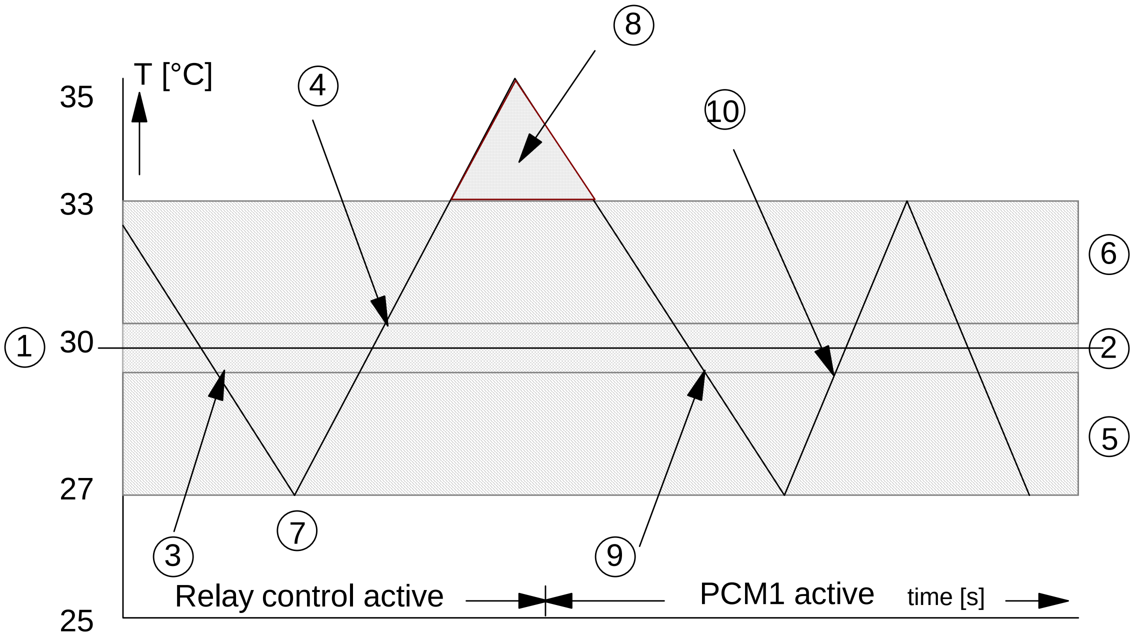


Figure 4: Predictive Control Mode 1

Figure 4 shows the course of the supply temperature in time of an imaginary heating system that is controlled initially by a relay controller.

✶ The desired supply temperature setpoint is set at 30 °C

✸ The dead band of the relay is set to 1 K, this means that:

✹ The valve opens when the controlled variable crosses the lower temperature limit of 29.5 °C downwards &

❈ The valve closes when the controlled variable crosses the upper temperature limit of 30.5 °C upwards

⊞ The amount of undershoot allowed is set to -3 K from the setpoint and

⌖ The amount of overshoot allowed is also set to 3 K from the setpoint.

✧ The relay controller keeps the undershoot within the allowable lower limit

☜ The overshoot is 5 K, this is 2 K too high. The PCM1 is now activated

☞ The PCM1 opens the valve at 29.5 ^{0}C. This is not changed; see ✹ and ✧.

✪ The overshoot is reduced by ‘earlier’ closing of the valve. This is determined by the following adaptive algorithm of the PCM1.

With the relay controller, after the valve is closed at 30.5 ^{0}C, the controlled variable has an overshoot of nearly 4.5 K. This is not acceptable. Thus, in order to reduce the maximum overshoot to 2.5 K, the PCM1 calculates the temperature at which the valve must be closed in the next period based on the last total measured overshoot according to:

$$33\ ^{\circ}\mathrm{C}_{\text{(max allowed)}} - 4.5\ ^{\circ}\mathrm{C}_{\text{(overshoot)}} = 28.5\ ^{\circ}\mathrm{C}_{\text{(next closing temperature)}}$$

In this case the PCM1 does not use fixed closing temperature but a variable one.

An other possibility to reduce the overshoot is by directly reducing the time that the valve is open. However, reducing the time that the valve is open by 50% will not result in a reduction of the overshoot by 50%, unless the system responses like a pure gain transfer function. Nevertheless, the actual dynamic behaviour of the fan coil unit is highly non-linear. A control strategy that reduces the valve open time must therefore have knowledge of the system’s dynamic behaviour. This brings along some disadvantages:

- Determination of the system’s dynamic behaviour is time consuming.
- A strategy based on a determined dynamic behaviour of the fan coil unit is vulnerable to unintended outcome and instability: changes in system parameters causes the fan coil unit to behave differently, for instance, when the flow of the water through the unit changes.

The PCM1 control strategy reduces the need to know the total dynamic system behaviour. Compared to this strategy the PCM1 strategy is less complex and more likely to remain stable. Moreover it can handle changes in the dynamic behaviour of the system. The PCM1 strategy has the following advantages:

- The concept is simple and can be implemented fast and at a low cost
- It adapts itself to parameter changes and disturbances.
- It can also be used on different types and sizes of fan coil units without modifications.

In some cases the PCM1 controller may lead to the desired control value in an iterative way. Consider a system with the same settings as shown in figure 4. Suppose the predicted overshoot is 4.5 K, but actually it is 5.5 K. This gives a maximum overshoot of 4 K:

$$28.5\ ^{\circ}\mathrm{C}_{\text{(valve closing value)}} + 5.5\ ^{\circ}\mathrm{C}_{\text{(actual rise)}} = 34.0\ ^{\circ}\mathrm{C}_{\text{(max measured supply temperature value)}}$$

So this time the controlled variable rises 5.5 K after the valve has been closed. Then the next time the valve will be closed by the PCM1 controller when the controlled variable has the next value:

$$33\ ^{\circ}\mathrm{C}_{\text{(max allowed supply temperature value)}} - 5.5\ ^{\circ}\mathrm{C}_{\text{(predicted rise value)}} = 27.5\ ^{\circ}\mathrm{C}_{\text{(valve closing value)}}$$

The system then generates, for instance, an actual rise of 6 K after the valve closes, giving a maximum overshoot of 3.5 K. The PCM1 controller uses this last value to determine the new value of the controlled variable at which the valve must close the next time and so on.
The actual rise generated by the system after the valve has been closed may also be smaller than the predicted rise value. The maximum amount of overshoot then lies within the allowed range of the overshoot. Still the PCM1 will try to achieve a maximum overshoot that approaches the desired overshoot. This assures stable control.

The PCM1 has a special feature that ensures the right opening and closing moments of the valve. Consider a system for which the controller determines to open the valve when the controlling variable has a value of 29.5 °C and to close the valve when the controlling variable has a value of 28.5 °C, see figure 5. Here we notice two moments at which the valve can open. Only one of these moments is the right moment, namely after the controlled variable has reached its maximum overshoot. The same holds for closing the valve. Here too the right moment for closing the valve is after the controlled variable has reached its maximum undershoot. The PCM1 continuously compares the current undershoot with the previous one. As long as the current undershoot is larger than the previous one, the maximum undershoot has not yet been reached and the PCM1 gives no permission to close the valve. The current overshoot is also compared to the previous one to determine of the right opening moment of the valve.

When the maximum undershoot is reached and the controlled variable is higher than 28.5 °C, the valve will be closed immediately. When the maximum overshoot is reached and the controlled variable is smaller than 29.5 °C, the valve will be opened immediately.

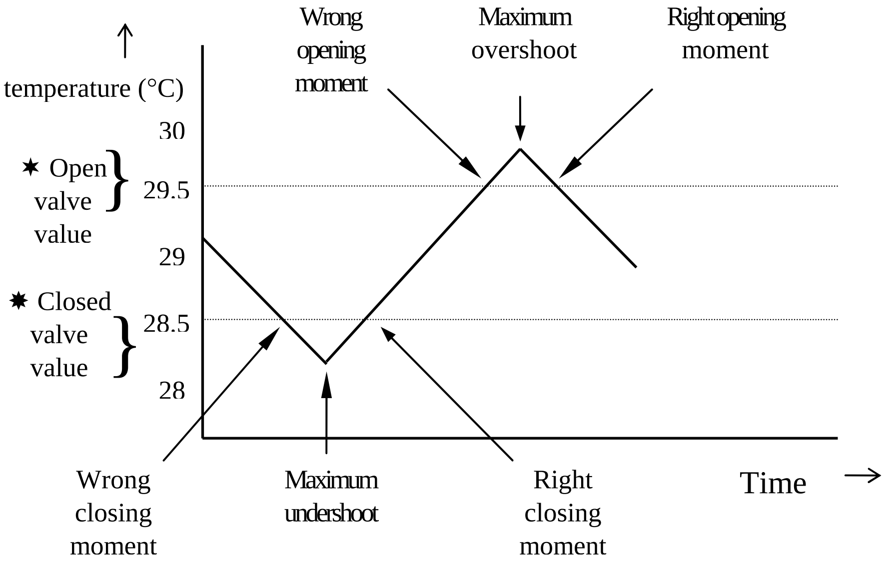
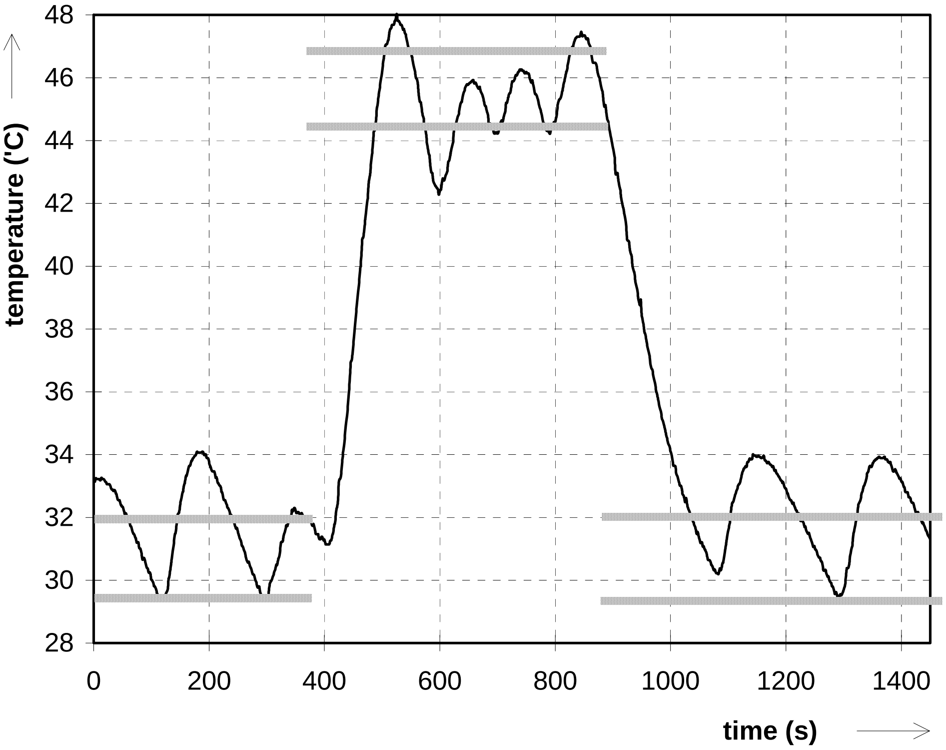


Figure 5: PCM1 valve’s opening and closing moments

The PMC1 was implemented and tested in the real system. The desired amount of overshoot was set at 2 K and the desired undershoot was set at 0.5 K. The desired supply temperature was set at 30 °C for 0 s < t < 350 s, at 45 °C for 350 s < t < 875 s, and at 30 °C again for 875 s < t < 1450 s. The results are shown in figure 6.

Figure 6: Test results with the PCM1



Compared to the relay controller the PCM1 works better: the overshoots and undershoots are reduced. Nevertheless, when the desired supply temperature is set at 30 °C, the overshoots of the supply temperature re are still unacceptable. In order to reduce these overshoots the valve must close 'earlier'. In this experiment the valve closes immediately after the controlled variable has reached its maximum undershoot. The features of the PCM1 do not allow the valve to close earlier. In this situation the overshoots can not be reduced by the PCM1 controller.

The strategy of the PCM1 may be extended to allow 'earlier' closing of the valve. This is explained in figure 7. The desired range of the controlled variable is 28.5 °C and 29.5 °C. Past and current system behaviours are represented by the solid line. The valve has just opened. The dashed line is the expected system behaviour. The valve closes immediately after the controlled variable has reached its maximum undershoot. This leads to a too high overshoot. The controlled variable rises 1.5 K after the valve closes; this is 0.5 K too much. The valve must thus be closed before the controlled variable reaches its maximum undershoot.

A possible control strategy is to close the valve when the controlled variable has a value as computed by the following equation:

$$28.5\ {}^\circ C_{\text{(max undershoot)}} + \{\, 1.5\ {}^\circ C_{\text{(predicted rise value)}} - 1\ {}^\circ C_{\text{(size desired controlled region)}} \,\} = 29\ {}^\circ C$$

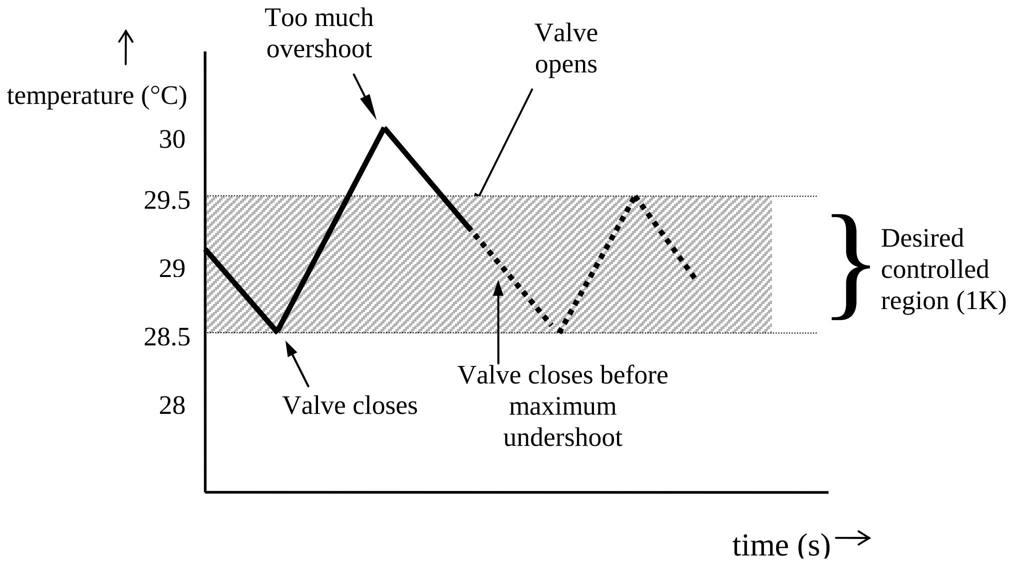


Figure 7: Possible extension on the PCM1 strategy

There are two points to be made concerning this control strategy:

1. The method works for systems that show a symmetrical behaviour when the valve is closed and when it is opened. Symmetrical behaviour takes place when the following two requirements are met:
   - the desired amount of overshoot ≈ the desired amount of undershoot
   - valve_open time ≈ valve_closed time

   Our fan coil unit does not meet these requirements.
2. The maximum undershoot used is a predicted maximum undershoot value since the real value is not yet available. Therefore the control of the overshoot depends on the accuracy of the prediction of the maximum undershoot making the control vulnerable to instability.

The following control strategy discussed, the PCM2, is designed to reduce the amount of overshoots and undershoots in the supply temperature for situations the PCM1 controller can not cope with. The PCM2 strategy works on systems showing asymmetrical behaviour and does not use predicted undershoot or overshoot values.

3.3 Predictive Control Mode 2 or PCM2

The PCM2 controller is always proceeded by the PCM1 controller just as the PCM1 is proceeded by the relay controller. As long as the PCM1 controller offers good control results it stays in control. The PCM2 takes over when the PCM1 controller closes the valve immediately after the controlled variable has reached its maximum undershoot. The PCM2 controller also makes use of past system behaviour to control it, just as the PCM1 controller. The PCM1 controller is an easy and satisfactory method for generating past system behaviours as is used by the PCM2 controller.

The PCM2 controls the supply temperature based on the same three setting as the PCM1:

1. The desired supply temperature
2. The desired or allowed amount of overshoot
3. The desired or allowed amount of undershoot

The PCM2 controller reduces the overshoots by reducing the time that the valve is in its open position. The time that the valve is opened is changed by a correction factor:

$$\text{valve\_open time}_{(new)} = \text{correction factor} \times \text{valve\_open time}_{(previous)}$$

For the fan coil unit the correction factor is chosen as a linear function of the difference of the measured and the set maximum overshoot:

$$\text{correction factor} = \text{constant} * (\text{measured max. overshoot} - \text{set max. overshoot}) + 1$$

When the measured maximum overshoot equals the set maximum overshoot the correction factor is 1 and the time that the valve stays open remains the same. When the measured maximum overshoot is higher than the set maximum overshoot, the correction factor has a value smaller than 1 and the time that the valve stays open is decreased and thus the overshoot is also decreased. A measured maximum overshoot that is smaller than the set maximum overshoot gives a correction factor higher than 1 and increases the time that the valve stays open. This will increase the overshoot.

Note that this control strategy uses the dimension of time. However, time is used only to adapt the time the valve is open. The strategy for the undershoot remains the same as for the PCM1. PCM2 ensures a far more stable control then PCM1, where the valve_open and valve_closed times are both adapted directly

.

The PCM2 controller was implemented in the real system. The desired supply temperature was set at 30 °C, the maximum undershoot at 0.5 K and the maximum overshoot at 1 K.
The results are shown in figure 8.

Between t = 400 s and t = 550 s the system was controlled by the PCM1 controller. The maximum undershoot is controlled precisely at 0.5 K and the maximum overshoot amounts to about 4 K which is 3 K too much. After t = 550 s the PCM2 controller takes over the control. Three overshoots later the maximum overshoot is reduced to about 1.5 K. These test results show that the PCM2 controller can also handle setpoint changes and changes in fan speed quit well.

The three control strategies were applied successively to control the supply temperature, see figure 9. The desired temperature was set to 30 °C. PCM2 was active between 0 s and 300 s. PCM1 controlled between 300 s and 700 s. Between 700 s and 1250 s the relay controller was in charge. Seen over a period of time, the PCM1 and PCM2 open and close the valve about twice as fast as compared to the relay controller.

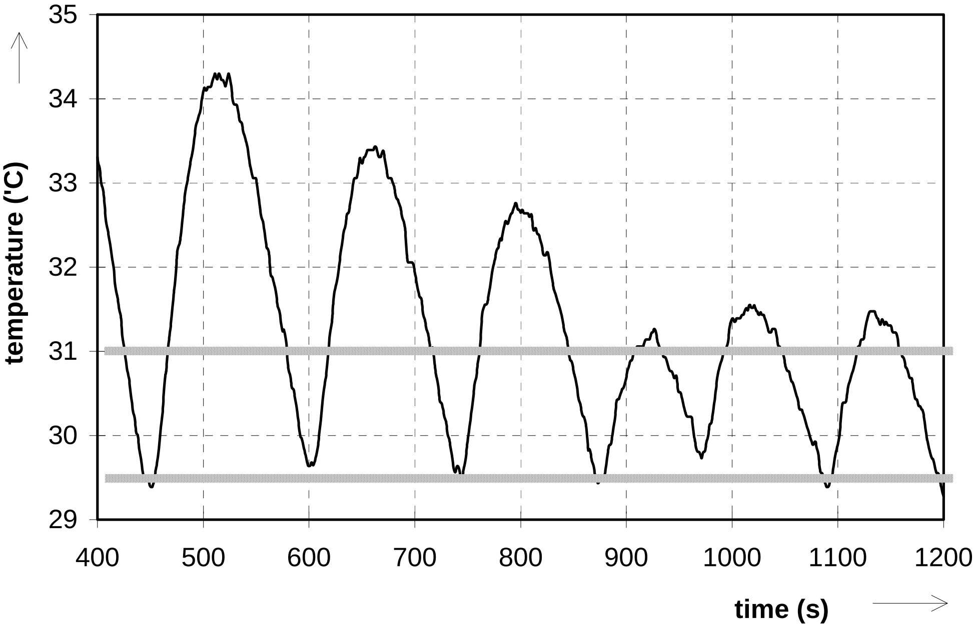


Figure 8: Test results PCM2 controller

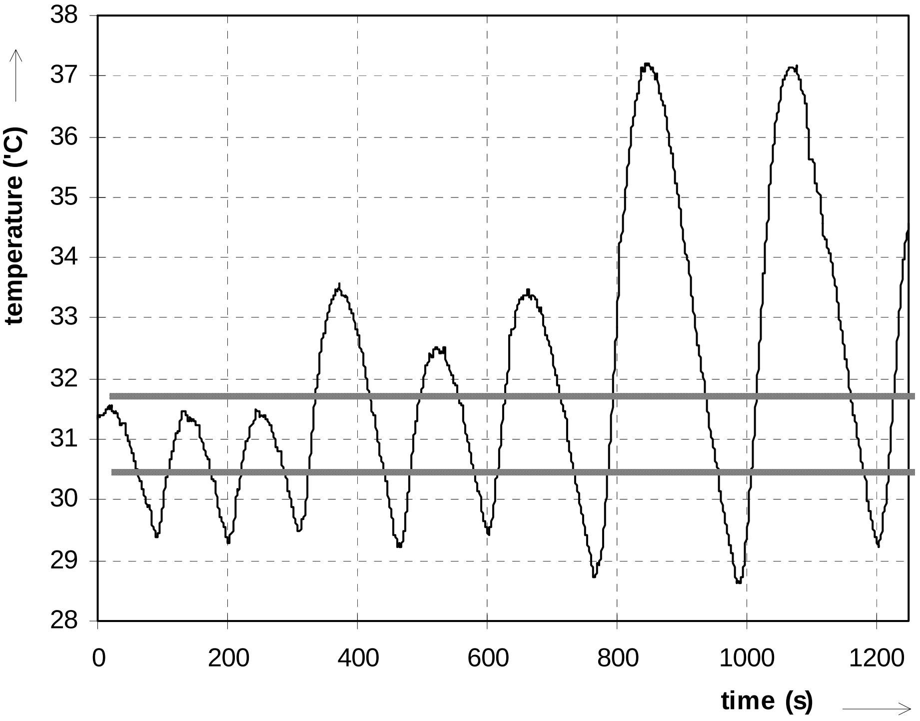


Figure 9: PCM2, PCM1, and Relay control applied consecutively

4. Conclusions

The control of the supply air temperature using on/off valves leads to unacceptable overshoots.

A rule based control method is proposed. Based on the control behaviour in the past control rules are adapted in order to reduce the overshoots to less then 1K.

The control method has been implemented in the control system of a fan coil unit and tested in a test room. The results show that fast and accurate control can be achieved with cheap on/off actuators.

The rule based control system is also applicable for other on/off control systems in HVAC.

Literature

[1] ASHRAE, Application handbook, chapter 41, Automatic control, 1991
[2] Lute, P.J, Control of fancoils by thermo regulated valves, simulations, control system tests, measurements of air flow patterns, noise measurements, Lab. voor Koudetechniek en Klimaatregeling, rapport K-205, Delft, 1994
[3] Lute, P.J. and A.H.C. van Paassen Optimal Indoor Temperature Control Using a Predictor , IEEE Control Systems, August, 1995, volume 15, number 4