Computer Control of Room Air Temperature by On-off Control of a Postheater

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Computer control of room air temperature by onoff control of a postheater

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COMPUTER CONTROL OF ROOM AIR TEMPERATURE BY ONOFF CONTROL OF A POSTHEATER

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This work has been a cooperation between the Department of Building Science and the Division of Automatic Control, Lund Institute of Technology, Lund, the Swedish Steam Users' Association (Angpanneföreningen), Malmö and Malmö General Hospital. The work is also a part of a research project supported by Grant D698 from the Swedish Council for Building Research.

Abstract

Control of room air temperature is studied for a pneumatic damper system and an electronic magnetic valve system. The study is carried out with a process computer. In the normal system the inlet air passes or bypasses a heatexchanger. In the second system the water flow through the heatexchanger is controlled by a magnetic valve.

This system is cheaper and controls the room air temperature better. It can also be economic to use a process computer in this system.

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1 Introduction

This report is a documentation of some experiments with an air postheater unit which supplies a one bed hospital room. The work is a cooperation between the Department of Building Science, the Division of Automatic Control (Lund Institute of Technology), Lund, the Swedish Steam Users' Association (Angpanneföreningen), Malmö and Malmö General Hospital (Malmö Allmänna Sjukhus).

The purpose with the work was to study the normal pneumatic control and different types of computer control using a magnetic valve.

The pneumatic system controls the amount of air that passes and bypasses the postheater. The air temperature is raised about 1.5 °C, when all air bypasses the postheater in the normal system. This is very costful, when the air has to be cooled during the summer and this can be avoided.

The computer control uses instead a magnetic valve which controls the amount of water that passes the postheater.

A short description of the room, the postheater and the experiment equipment is given in section 2.

In section 3 some simple models are derived based on construction data and on simplifying assumptions. This is done to see if it is possible to determine suitable models in this way without making any experiments.

In section 4 an identification method of least squares is used to determine models. Discrete time models are given for the best models.

In section 5 regulators are determined by simulation by Ziegler Nichols rule and by using linear quadratic control theory.

In section 6 some fullscale experiments are documented. A certain test run is used in all experiments. The open loop system, the normal regulator and digital onoff ratio regulators are tested.

In section 7 comparisons are made between simulated and fullscale experiments.

In section 8 costs are calculated for different postheater systems.

Finally, in section 9 some conclusions from the experiments and calculations are discussed.

2 The process

2.1 The room

The room is a one bed hospital room in a long time treatment clinic at Malmö Östra Sjukhus. The building was finished in 1974. A picture of the room is given in figure 2.1. Some data about the room are

room number	2069
length	4.6 m
width	3.0 m
height	2.6 m
volume	36 m^3
number of airchanges	4.7/h
window area	2.7 m^2

The room was unfurnished. The walls and the ceiling are made of gypsum plasterboard on studs.

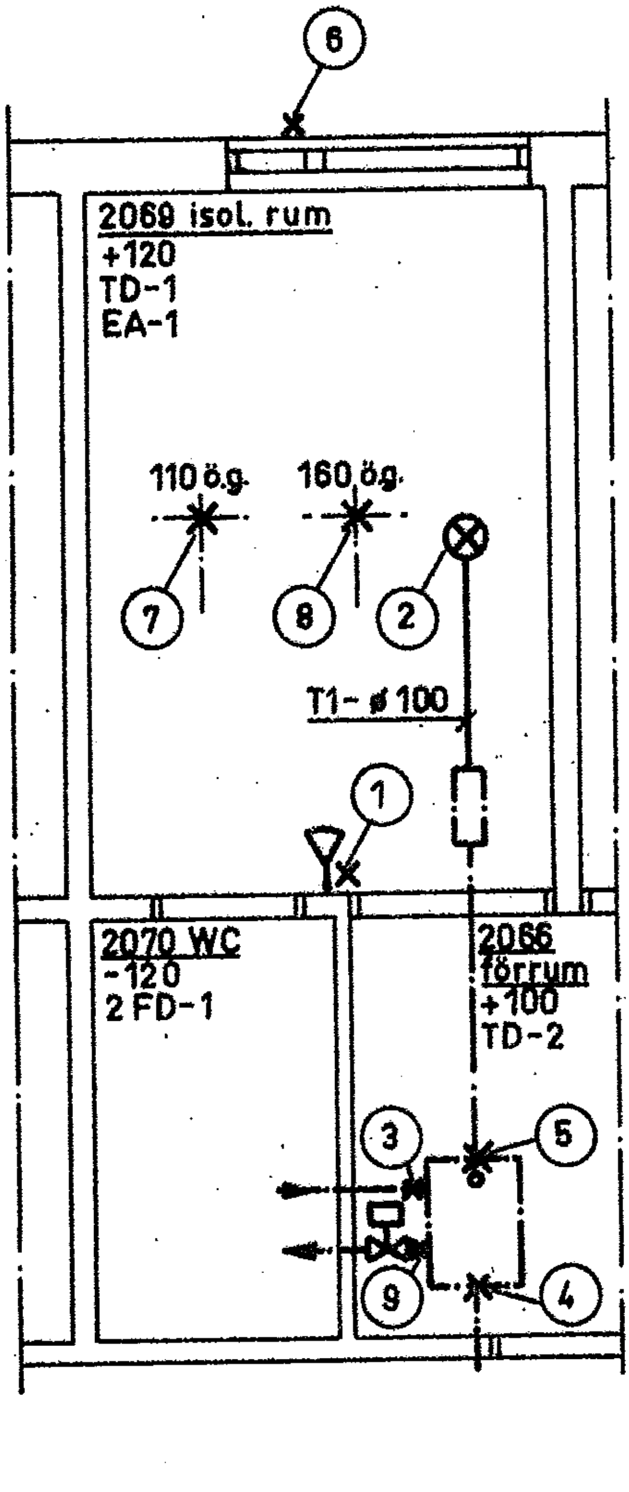

Figure 2.1 Room, postheater and temperature measurement points.
Scale 1:50.

2.2 The postheater

The postheater consists of a heatexchanger and a pneumatically operated damper. The damper controls the air flow ratio between the air that passes the heatexchanger and the air that bypasses it. A picture of the postheater is given in figure 2.2. The water flows constantly through the heatexchanger in normal operation.

Some data is given below

mark	SF RBJB-2-1-1-2-1-2-0
air flow (dim)	120 m^3/h
water flow (dim)	0.075 m^3/h
air flow (measured)	170 m^3/h
water flow (measured)	0.080 m^3/h
water inlet temperature (dim)	60 ^oC
water outlet temperature (dim)	50 ^oC
air inlet temperature (dim)	13 ^oC
air outlet temperature (dim)	25 ^oC
heatexchanger water mass	0.2 kg
heatexchanger copper mass	0.5 kg
heatexchanger aluminium mass	1.8 kg
heatexchanger metal to air surface	2.7 m^2
total weight	18.5 kg

The air temperature can then be increased about 1.5 ^oC by heatlosses from the heatexchanger, when the damper has closed completely for the heatexchanger.

This heatloss can be eliminated by instead using a valve to control the water flow. The damper is fully opened in this case. Valves that can control water flows of the actual size can hardly be found. A magnetic valve can be used instead. A continuous valve position can be implemented by using a pulse length modulated two state control signal $u_p(t)$.

The pulselength modulated control signal $u_p(t)$ can be given as follows, if the normal control signal is in the interval (0.0, 1.0) and the period time is T.

$$u_p(t) \doteq \begin{cases} 1 & n\,T \leq t < (n + u(t))\,T \\ . & \\ 0 & (n + u(t))\,T \leq t < (n + 1)\,T \end{cases} \qquad n=1,2,3,\ldots..$$

This is called onoff ratio control.

A pneumatic room air temperature sensor controls the damper. This system has a fixed P band of 1.8 ^oC. The system is not purely proportional but it can be considered as a first order system with a gain of $(1.8\ ^oC)^{-1}$ and a time constant of about 10 minutes.

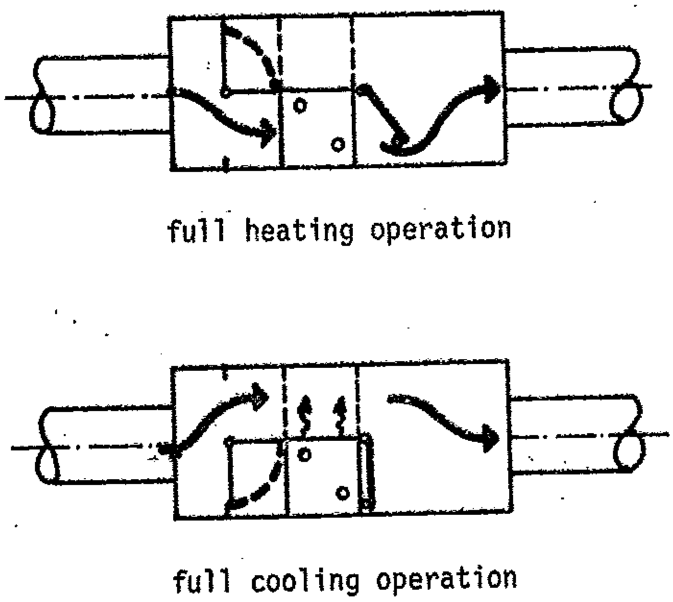

Figure 2.2 The postheater is shown in full heating and full cooling operation

2.3 The measurement and control equipment

The measurement and the control were carried out by a coupler/controller unit (Hewlett Packard) connected to a process computer. The c/c can measure 10 analog inputs and control 4 analog and 4 logical outputs. 5 analog inputs were connected to thermistor bridges for 15-35 °C and 5 for 0-100 °C. Further details are given in Jensen (1973).

The exact location of different temperature sensors is given in figure 2.1 and appendix 1. The room air temperature sensor has been situated 50 mm below the normal pneumatic room air temperature sensor.

2.4 The process computer and programs

The process computer PDP-15 (Digital) has 32 k core memory, one 256 k disc, three dectape units, three teletypes and a display. All experiments were carried out with the realtime executive RSX-plus.

Computer programs controlled the measurements, generated the input sequence and set out the control signal.

All inputs and outputs were logged. These could also be displayed on-line.

2.5 The communication link

The process computer is situated at the Division of Automatic Control, Lund Institute of Technology, Lund and the one bed hospital room at a long time treatment clinic at Malmö Östra Sjukhus. Low-speed modems (max 200 baud) were used as communication line. Both the computer and c/c used teletype-speed (110 baud), which is equivalent to ten ASCII characters per second. Measuring all inputs and controlling all outputs will take about 30 seconds.

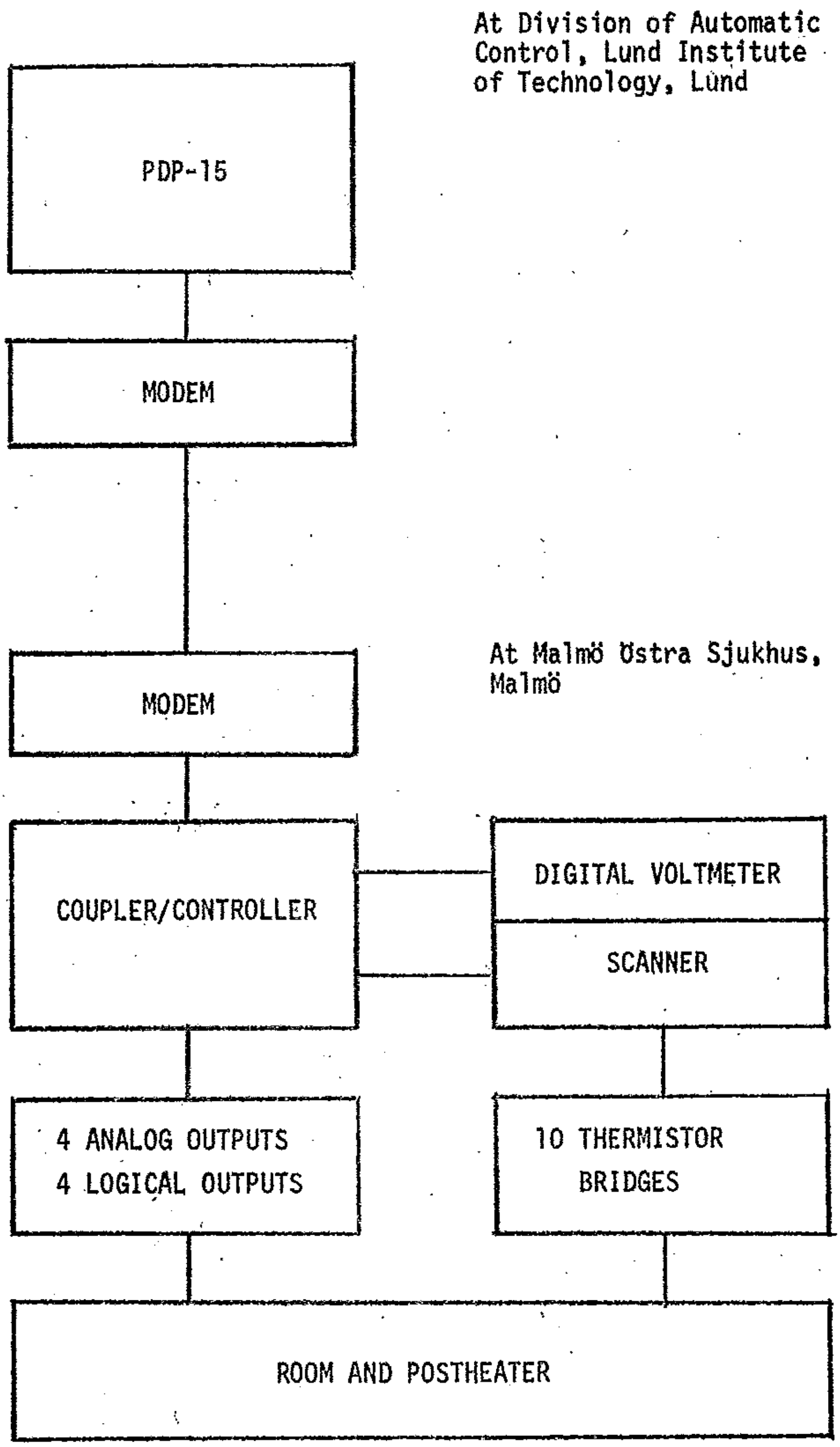

Figure 2.3 The process

3 Simple models based on construction data

The purpose with this section is just to get some very crude estimates of static gains and main time constants of difficult parts of the process. One model is obtained for the postheater and another for the room. Transportation delays will be omitted.

3.1 A model of a postheater

A very simple compartment model of the postheater is considered. The model is shown in figure 3.1

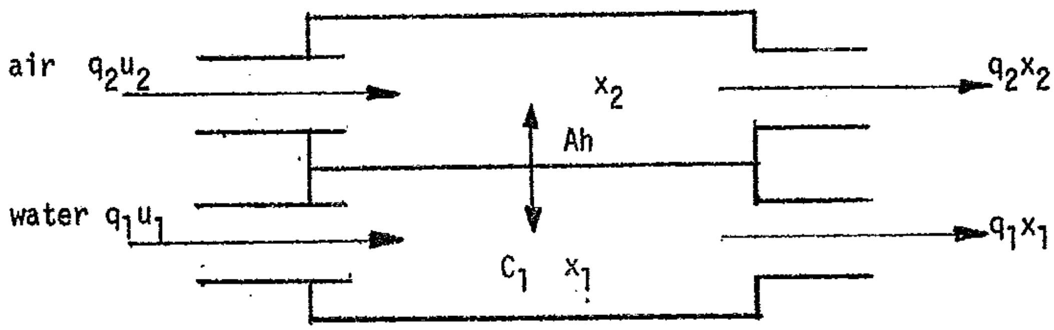

Figure 3.1 A compartment model of a postheater

The following assumptions are made in the model:

1 The water and metal masses have the same temperature all over in the postheater

2 The air temperature is the same all over in the postheater

3 The heat transfer between water-metal to air is assumed to be proportional to the temperature difference

4 The air is assumed to have no mass

The following notations are used:

$x_1(t)$ water-metal temperature
$x_2(t)$ air temperature
$u_1(t)$ inlet water temperature
$u_2(t)$ inlet air temperature

One heatbalance equation can be derived for each compartment. These are as follows:

$$C_1 \dot{x}_1(t) = -(Ah+q_1)x_1(t) + Ah\ x_2(t) + q_1\ u_1(t) \tag{3.1}$$

$$0 = Ah\ x_1(t) - (Ah+q_2)x_2(t) + q_2\ u_2(t) \tag{3.2}$$

The model parameters are as follows:

C_1 water-metal heat capacity
q_1 water heat capacity flow
q_2 air heat capacity flow
Ah total heat transfer coefficient between water-metal and air

The equations (3.1) and (3.2) are nonlinear if the flows q_1 and q_2 are used as inputs. Two sets of equations (3.1) and (3.2) have to be used, when onoff ratio flow control is simulated. Instead the flow q_1 is assumed to be continuous and constant in the future analysis.

The transfer function between the water temperature $u_1(t)$ and the air temperature $x_2(t)$ can be computed as

$$G(s) = \frac{K_1}{sT_1+1} \qquad (3.3)$$

Where

$$K_1 = \left(1 + \frac{q_2}{Ah} + \frac{q_2}{q_1}\right)^{-1}$$

$$T_1 = \frac{C_1(Ah + q_2)}{(Ah(q_1+q_2)+q_1q_2)}$$

This transfer function can be used to study how the static gain K_1 and the timeconstant T_1 depends on the water heat capacity flow q_1.

The model parameters have been measured and computed as follows:

$C_1 = 2600\ J/^oC$
$Ah = 23\ W/^oC$
$q_{1_{max}} = 93\ W/^oC$
$q_2 = 57\ W/^oC$

The ratio K_1/K_{1max} is computed as a function of q_1/q_{1max}. The result is shown in figure 3.2. The curve shows the well known fact that the air temperature raise over heat exchanger is a nonlinear function of the water flow.

The timeconstant T_1 varies from 26 minutes to 4 minutes corresponding to the flows from $q_1 = 0$ to $q_1 = 93\ W/^oC$.

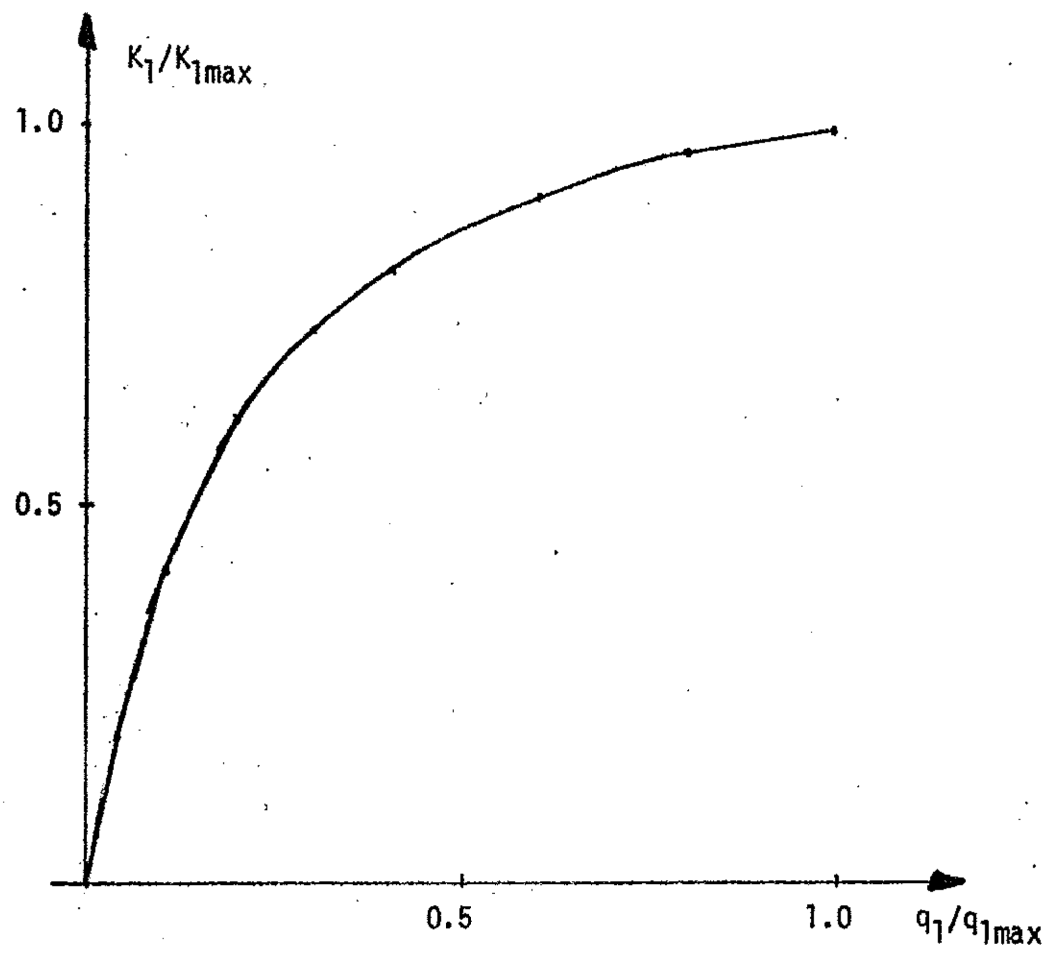

Figure 3.2 The ratio K_1/K_{1max} in transfer function (3.3) as a function of the water heat capacity flow ratio q_1/q_{1max}.

3.2 A room model

A very simple first order model for the input-output system inlet air temperature to room air temperature can easily be obtained if the room air is assumed to be totally mixed and the heated air, the walls (the ceiling, the floor and the furniture is supposed to be included in "walls") and the outdoor air temperature are assumed to be inputs and not affected by the room air temperature.

The assumption that the temperature of the walls is not affected by the room air temperature may be a good approximation if the heat capacity of the walls is far larger than the heat capacity of the room air. Then the wall temperature will only change very slowly and with small amounts.

The heat balance equation becomes:

$$C\dot{x}(t) = -(nC + Ah)x(t) + nCu_1(t) + Ahu_2(t)$$

Here is $x(t)$ = room air temperature
- $u_1(t)$ = inlet air temperature
- $u_2(t)$ = other temperature inputs
- A = surface between room air and walls
- C = room air heat capacity
- h = heat transfer coefficient for surface A
- n = the number of room air changes per time unit

If the heat balance equation is Laplace transformed one will get the transfer function between the input u_1 and the output $x(t)$ as:

$$G_1(s) = \frac{K_2}{sT_2 + 1}$$

The relations between parameters in the heat balance equation the ones in the transferfunctions are:

$$T_2 = C/(nC + Ah)$$

$$K_2 = nC/(nC + Ah)$$

Crude calculations gives:

$$nC = 57\ W/^{o}C$$
$$C = 43000\ Joule/^{o}C$$
$$Ah = 120\ W/^{o}C$$

which gives

$$T_2 = 4.0\ min$$
$$K_2 = 0.32$$

4 Identification

In this section different models will be studied using experimental data.

4.1 Determination of postheater nonlinearity

A nonlinear process is difficult to control. As mentioned previously, the temperature raise over a water to air heatexchanger is a nonlinear function of the flow. The water temperature is assumed to be constant.

The characteristics of the nonlinearity of a process can be determined by a simple static experiment. The input is the onoff ratio of the magnetic valve and the output is the air temperature after the postheater. The onoff ratio, the air temperature before and after the postheater and the primary water temperature have been measured in some experiments.

The air temperature raise over the postheater is plotted against the onoff ratio in figure 4.1. The result should also be compared with the theoretic curve in figure 3.2.

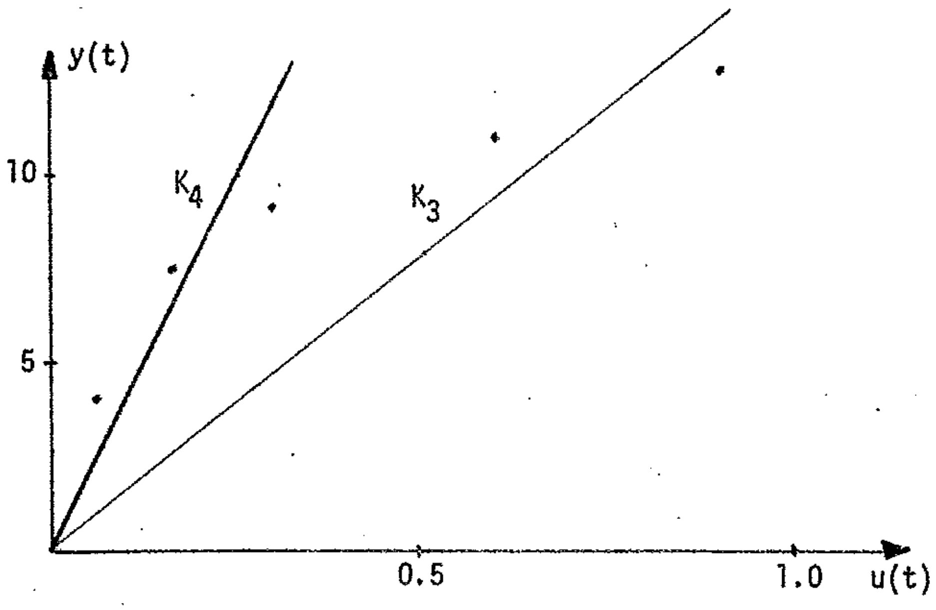

Figure 4.1 Air temperature raise y(t) in °C over postheater as a function of onoff ratio u(t).

4.2 Identification experiment

To be able to identify the dynamics of a process, a suitable input signal has to be chosen. This was done by using a PRBS (Pseudo Random Binary Sequence) signal. Details about the PRBS signal can be found in Davis (1970). The signal sequence assumes only two values. The input signal was the onoff ratio to the magnetic valve.

The two used onoff ratios were 0% and 100%. The shortest and longest period were 10 minutes and 50 minutes. The experiment was interrupted after 110 minutes or 110 samples. The window radiators were turned off. The input and the output are shown in figure 4.2.

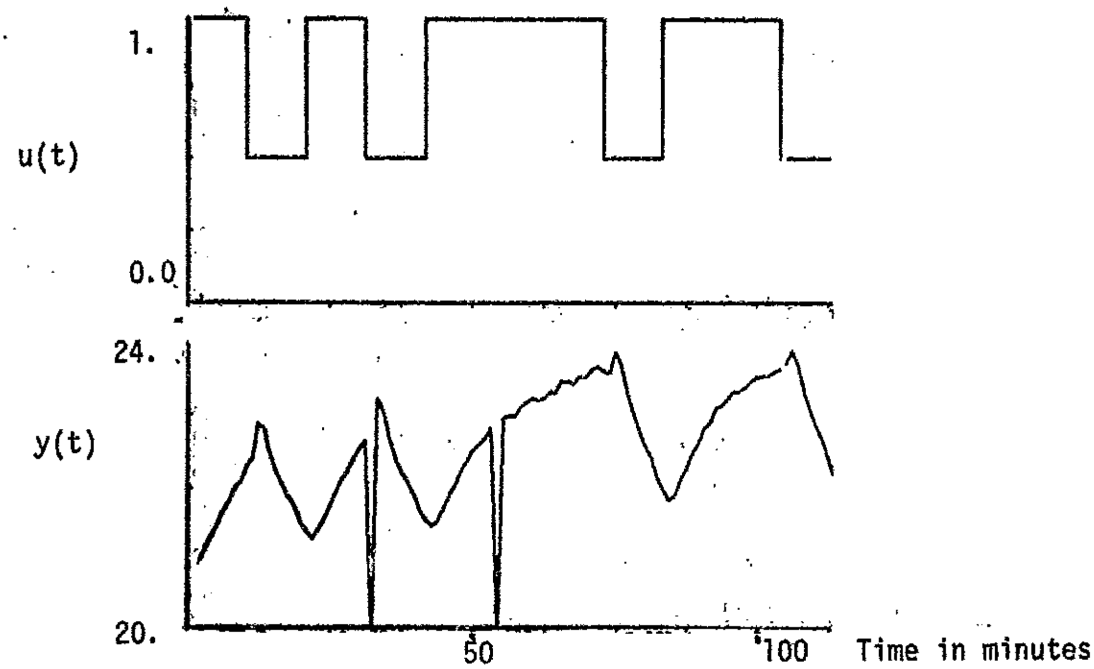

Figure 4.2 Identification experiment. u(t) is the onoff ratio and y(t) is the room air temperature in ^{o}C.

4.3 Model and identification method

Using the experimental data described above, the dynamics from the onoff ratio (denoted by $u(t)$) to the room air temperature (denoted by $y(t)$) was modelled as follows. First the coefficients of a difference equation

$$y(t) + a_1 y(t-1)+\ldots+a_n y(t-n) = b_1 u(t-k-1)+\ldots+ + b_n u(t-k-n) + v(t) \tag{4.1}$$

were determined using a least squares criterion. The model parameters a_i and b_i are thus found by minimizing the loss function

$$V = \sum_{t=1}^{N} v(t)^2 \tag{4.2}$$

Further details about the method are given in Åström (1968).

The identification was performed using the identification program package IDPAC, see Gustavsson, Selander and Wieslander (1973).

4.4 Identification results

Using the technique outlined in section 4.3 models of first, second and third order have been determined from the experiment, shown in figure 3.2. The delay parameter k has been 0, 1,2 and 3.

The best model after that the mean values have been subtracted from the input and the output is as follows:

$$y(t) - 0.958\, y(t-1) + 0.052\, y(t-2) = = 0.241\, u(t-3) + 0.084\, u(t-4) \tag{4.3}$$

The lossfunction was V = 2.86 which corresponds to a standard deviation of the modelerror $v(t)$ of 0.16 ^oC.

A still better model is obtained when a trend in the output is removed. The model then is as follows:

$$y(t) - 1.053\ y(t-1) + 0.152\ y(t-2) = \\ = 0.245\ u(t-3) + 0.048\ u(t-4) \qquad (4.4)$$

The lossfunction was V = 1.29 which corresponds to a standard deviation of the modelerror v(t) of 0.11 °C.

The model output and the measured output are both shown in figure 4.3 for model (4.4).

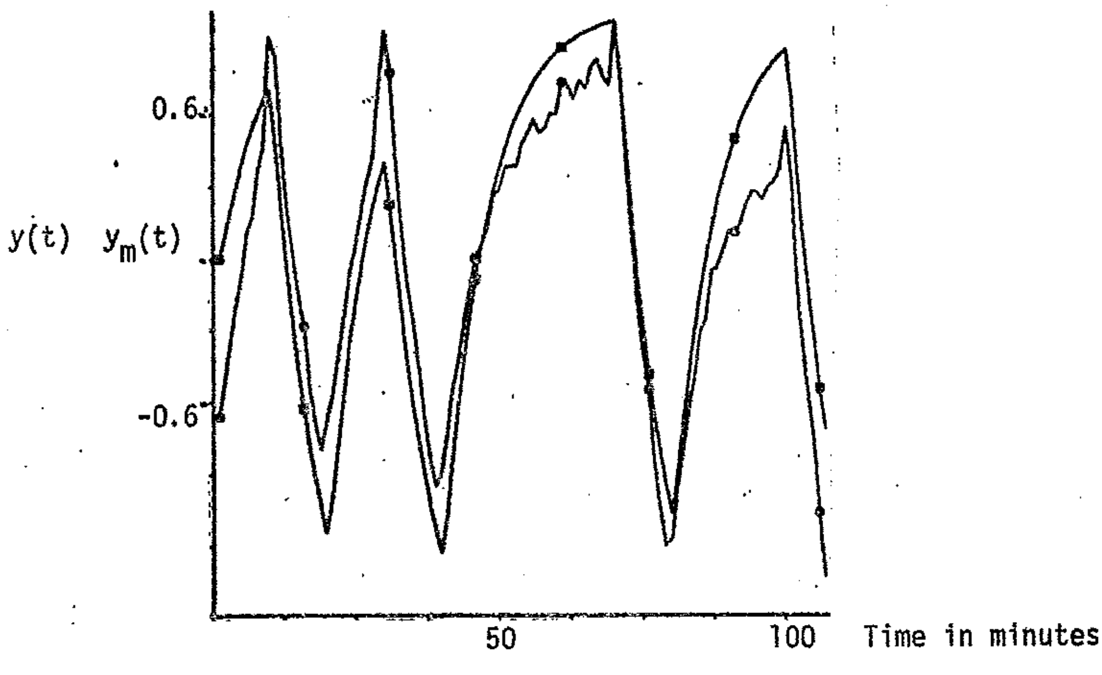

Figure 4.3 Measured output y(t) (rough line) and model output $y_m(t)$ smooth line) from model (4.4) both in °C.

4.5 Comparison between the model gain and the nonlinearity

In section 3.1 and 4.1 it was found that the postheater is nonlinear with the flow as input. If the model gain is considerably smaller than the nonlinearity given in figure 4.1, then the designed closed loop system might be unstable.

The static gain between the onoff ratio and room air temperature is computed to the following average value from models (4.3) and (4.4)

$$K_1 = 3.23\ ^{o}C$$

The static gain between the inlet air temperature and the room air temperature has been identified to

$$K_2 = 0.20$$

The static gain between the onoff ratio and inlet air temperature is computed as follows

$$K_3 = \frac{K_1}{K_2} = 16\ ^{o}C$$

This value should be compared with the slope of line K_4 in figure 4.1 which corresponds to

$$K_4 = 40\ ^{o}C$$

This value K_4 is considerably larger than K_3. This indicates that regulators based on the model might be unstable.

The process gain is also affected by the hot water temperature and the preheated air temperature.

5 Determination of regulators

In this section we will determine regulators that control the room air temperature using the onoff ratio to the magnetic valve as input.

The purpose of the control is to maintain a constant room air temperature under various disturbances. Some of the most important disturbances may be the following:

Outdoor air temperature
Sun radiation
Wind
Persons
Illumination
Machines
Change of room air
Random air circulations

Some of the disturbances appear more or less like step disturbances, while the heating process has a slow response. Since feedforward terms are not feasible, the control cannot be able to eliminate the disturbances without some overshoot.

If a window is opened for a short while the temperature usually changes quickly. But the heat capacity in walls, ceiling and floor together is in many cases 100 times larger the heat capacity of the room air. Therefore the air temperature resumes its old value even without control, due to heat exchange with the walls, ceiling and floor. Consequently the control law should react differently on this kind of disturbance than on a more long term disturbance like change of outdoor temperature. The temperature noise due to random air circulations must also be regarded when a control is designed.

The process under consideration is quite slow. It takes several hours to evaluate the performance of a regulator. Thus even the tuning of a straightforward PID regulator will be very time consuming. Consequently, simulation of different control laws on a good mathematical model of the process saves a lot of time. Also, more complex regulators may have to be used. This is often the case when there are time delays in the system. To determine such regulators a model is very valuable. Optimal control laws can be synthesized from the model, applying e.g. Linear Quadratic control theory.

The regulators have been developed and tested using the interactive computer program package SYNPAC and the model (4.4) given in section 4.3 for about 2.5 hours. The program package is described in Wieslander (1973).

The derivative is implemented as follows

$$\dot{y}(t) = y(t) - y(t-1)$$

The sum of y(t) is used as integral and is denoted

$$\tilde{y}(t) = \sum_{i=0}^{t} y(i)$$

First a PI and a PID regulator are tuned by a trial and error method (section 5.1). A comparison is made with regulators obtained by the Ziegler Nichols rule. The critical gain and frequence were found by simulation (section 5.2).

Linear quadratic control theory has also been used to obtain regulators (section 5.3). The procedure is the same as in Jensen-Ljung (1973a).

All regulators have been tested with a pulse disturbance added to the output signal. The response of the open loop system to this disturbance is shown in figure 5.1.

5.1 PID regulators tuned by simulation

The coefficients of a standard PID regulator were chosen on the basis of simulation. Suitable P, PI and PID regulators turned out to be

P regulator

$$u(t) = -0.4\ y(t) \tag{1}$$

PI regulator

$$u(t) = -0.4\ y(t) - 0.05\ \tilde{y}(t) \tag{2}$$

PID regulator

$$u(t) = -1.\ y(t) + 0.5\ y(t-1) - 0.06\ \tilde{y}(t) \tag{3}$$

The responses of the closed loop systems obtained with these regulators are given in figure 5.2 and 5.3

5.2 PID regulators based on Ziegler Nichols rule

The critical gain and frequence were found by simulation. The gain was found to be 1.34 ^{o}C and the frequence 0.47 rad/min. The regulators turned out to be

P regulator

$$u(t) = -0.67\ y(t) \tag{4}$$

PI regulator

$$u(t) = -0.60\ y(t) - 0.055\ \tilde{y}(t) \tag{5}$$

PID regulator

$$u(t) = -2.13\ y(t) + 1.33\ y(t-1) - 0.12\tilde{y}(t) \tag{6}$$

These regulators are somewhat similar to the former PI and PID regulators tuned by simulation. The closed loop responses are given in figure 5.2 and 5.4.

5.3 Regulators obtained from linear quadratic control theory

Linear quadratic control theory was applied to the model (4.4) in the same way as described in Jensen-Ljung (1973). The loss-function was chosen as follows

$$V = \sum_{t=0}^{\infty} q_1\, y^2(t) + q_2\, \tilde{y}^2(t) + u^2(t)$$

where q_1 and q_2 are suitable constants.

Choosing different values on q_1 and q_2 shows that the maximum deviation of the output could not be made as small as wanted. This is mainly due to the delay of two minutes in the system.

A suitable response of the closed loop system was achieved with $q_1 = 0.01$ and $q_2 = 0.01$. The corresponding regulator is:

$$\begin{aligned} u(t) = & -0.708\, y(t) + 0.103\, y(t-1) \\ & -0.092\, \tilde{y}(t) - 0.18\, u(t-1) \\ & -0.19\, u(t-2) - 0.20\, u(t-3) \\ & -0.03\, u(t-4) \end{aligned} \qquad (7)$$

Another regulator with $q_1 = 0.1$ and $q_2 = 0.1$ was as follows:

$$\begin{aligned} u(t) = & -1.73\, y(t) + 0.24\, y(t-1) - 0.26\, \tilde{y}(t) \\ & -0.38\, u(t-1) - 0.42\, u(t-2) \\ & -0.47\, u(t-3) - 0.08\, u(t-3) \end{aligned} \qquad (8)$$

The closed loop responses are shown in figure 5.5.

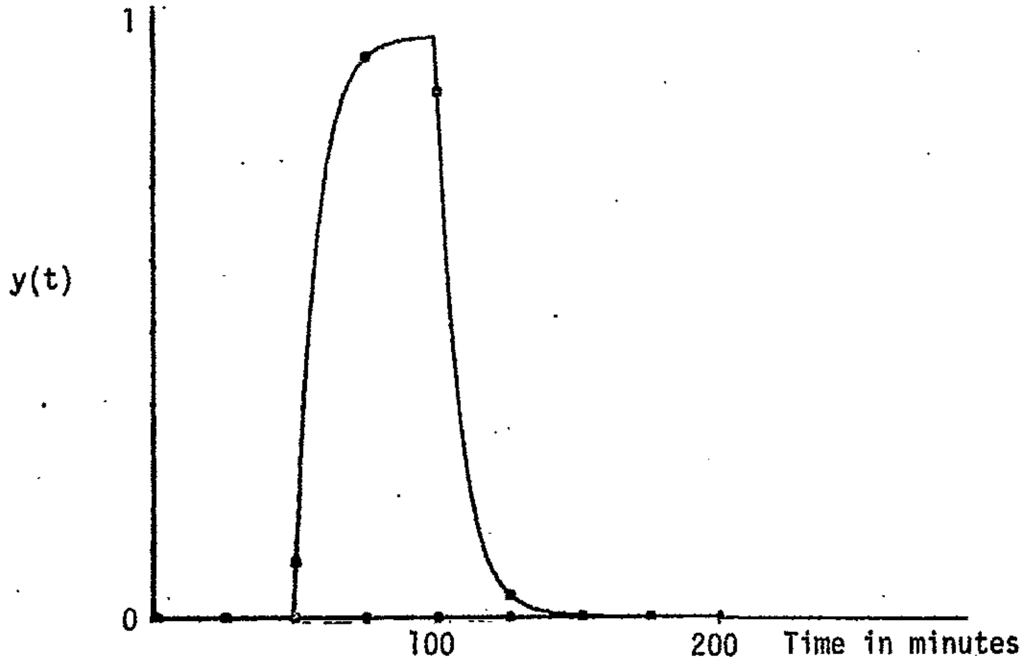

Figure 5.1 Simulation of open loop system. y(t) is the room air temperature in ^{o}C.

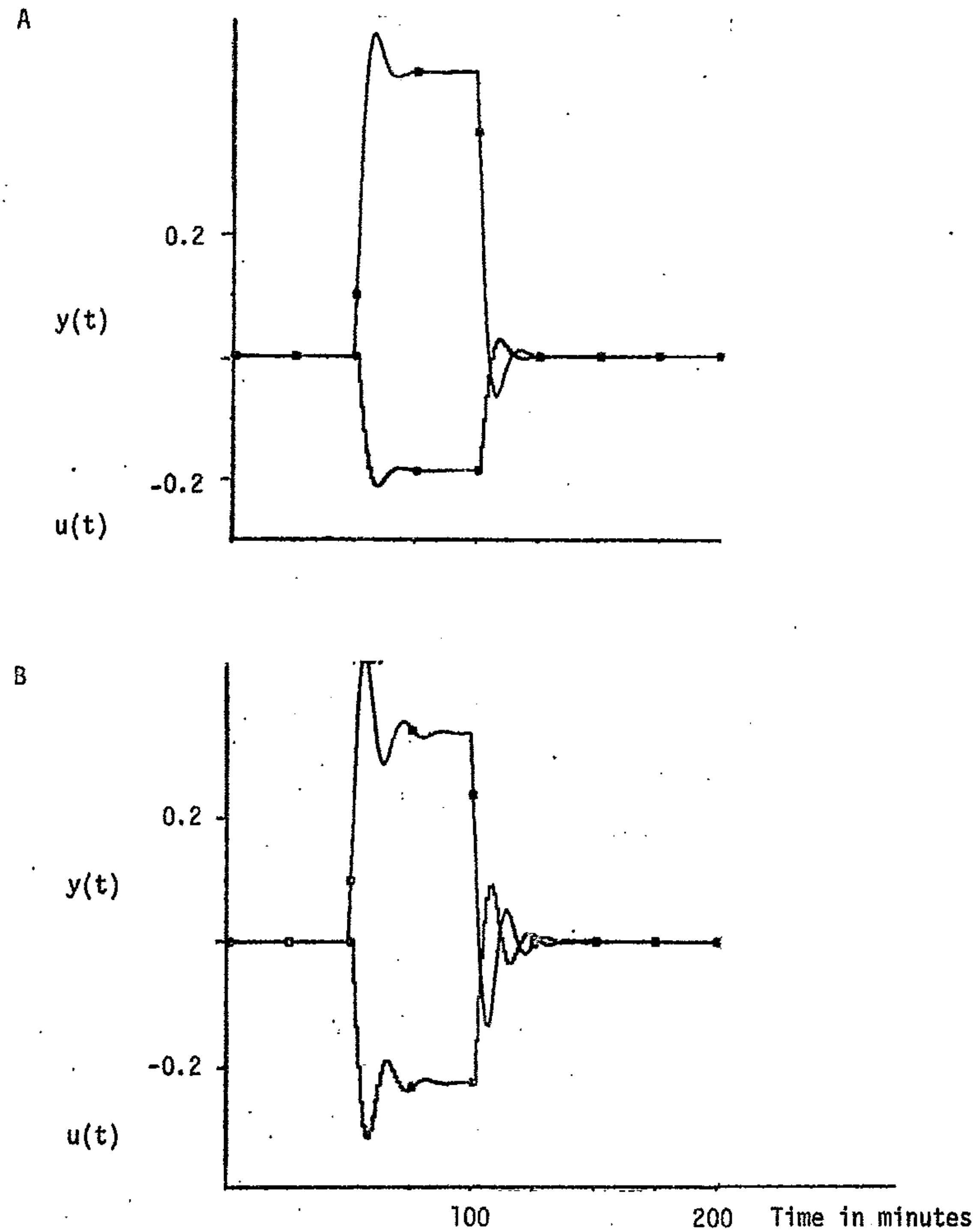

Figure 5.2 Simulation of P regulators A(1) and B(4). u(t) is the onoff ratio and y(t) is the room air temperature in ^{0}C.

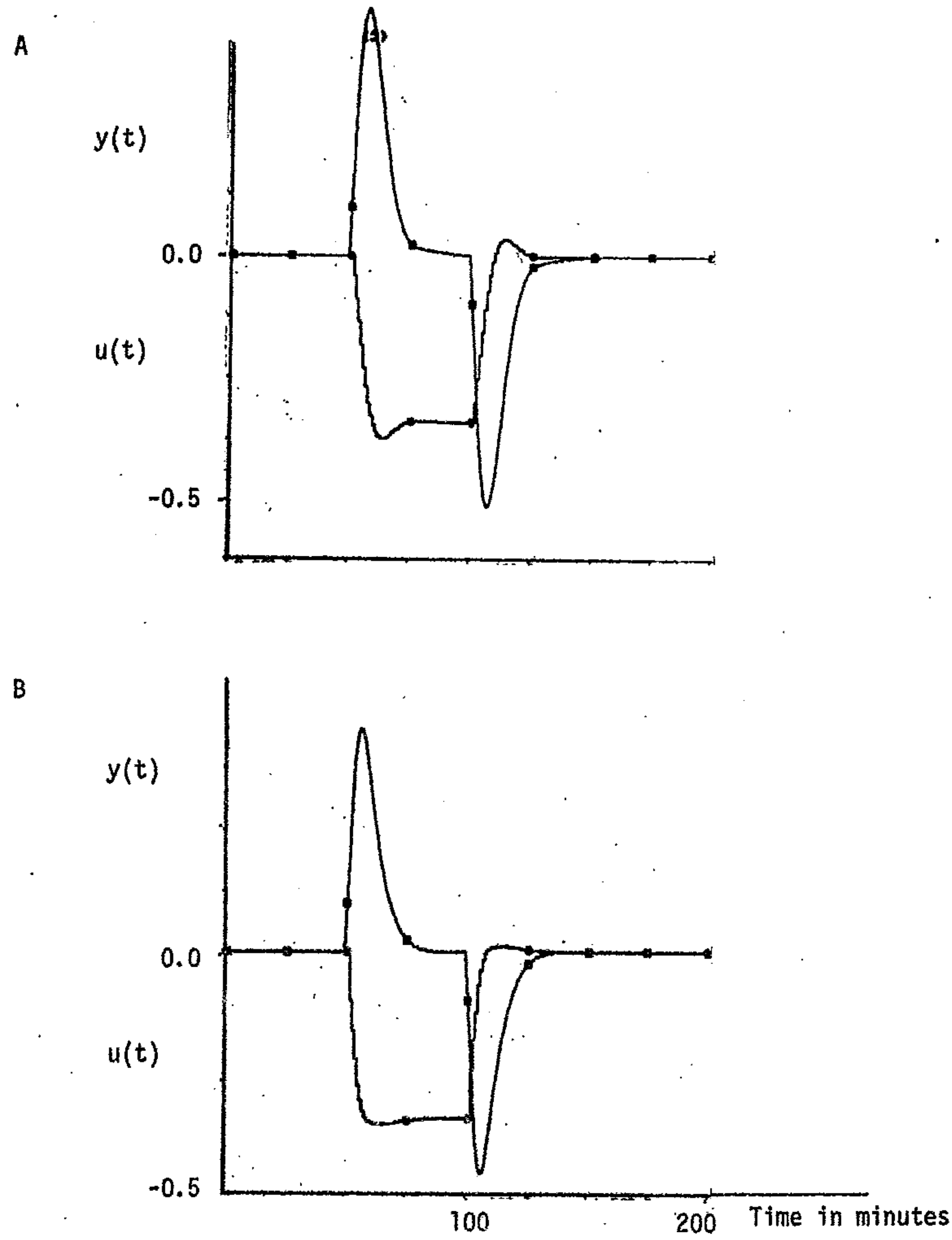

Figure 5.3 Simulation of PID regulators tuned by simulation A(2) and B(3).

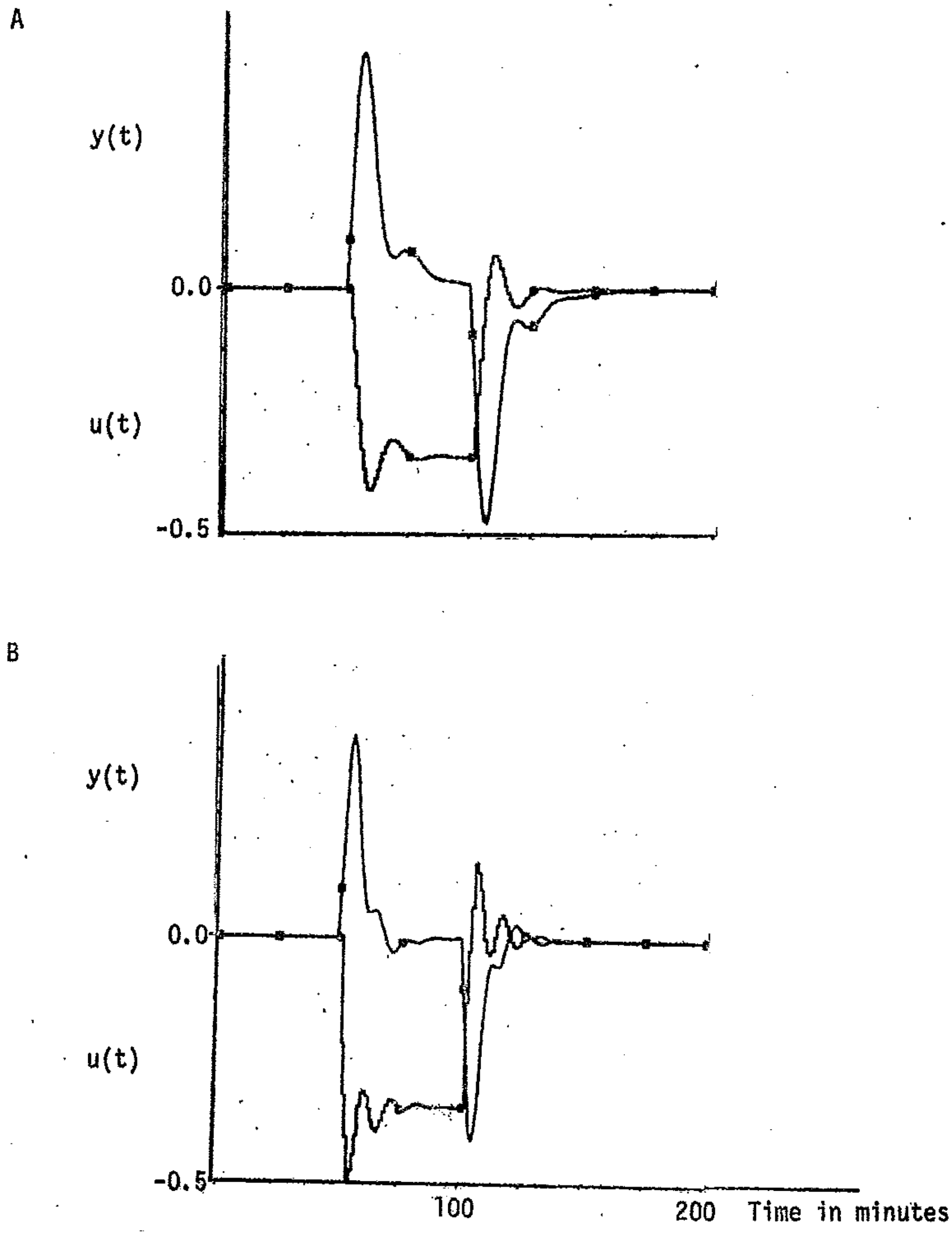

Figure 5.4 Simulation of PID regulators based on Ziegler Nichols rule A(5), B(6). u(t) is the onoff ratio and y(t) is the room air temperature in ^{o}C.

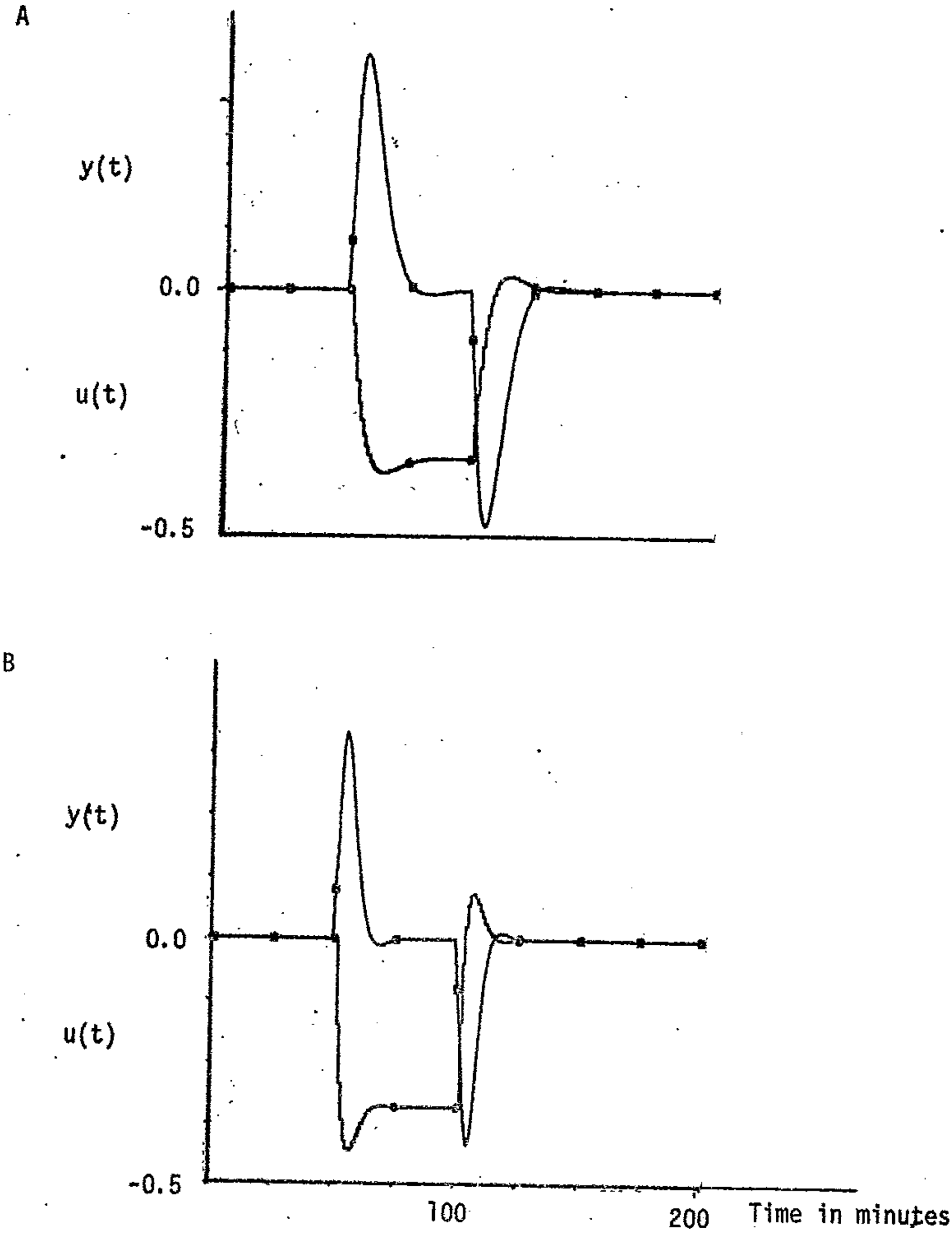

Figure 5.5 Simulation of linear quadratic regulators A(7) and B(8). u(t) is the onoff ratio and y(t) is the room air temperature in ^{0}C.

6 Fullscale control experiments

To test a control law it would be convenient to artificially generate some of the earlier discussed disturbances in a full scale experiment. This has been done with a test run of 100 minutes duration. Four 100 W light bulbs in the room were turned on between the 30th minute and the 60th minute. The heating effect was then 400 W. The air conditioning is dimensioned to compensate a heat load of about 450 W at a room air temperature of 23 ^{o}C and an inlet air temperature of 15 ^{o}C.

The magnetic valve is of course open, when normal control is tested. The damper is fully opened, when onoff ratio control is tested.

All regulators implemented on the computer were subject to the following conditions.

The sampling interval has been 1 minute throughout all experiments.

The period time for the onoff ratio regulators were 1 minute.

The derivative of the output y(t) has been implemented as the difference y(t) - y(t-1).

The integral of the output y(t) has been implemented as the sum

$$\tilde{y}(t) = \sum_{i=0}^{t} y(i)$$

The integral term in the controllers was not updated when the computer control signal was outside the interval (0.,1.). The integral can be interpreted as a control signal setpoint value. It is then natural not to update the integral when the control signal is on either limit.

The integral has not been zeroed, when the regulator was started. The start value has been the one that the preceeding regulator has left.

No data filtering has been made in any of the regulators. The temperature measurement accuracy is better than ±0.05 °C.

Some errors occurred in the room air temperature y(t) during the control experiments. The regulator program detected these errors and used the latest accepted value.

The total time of real time processing is about 34 hours and 15 hours are shown in figures.

The different types of control experiments will be presented in the subsections.

6.1 The open loop system

The open loop system has been run with a pulse length modulated control signal u(t)=0.6. The result is given in figure 6.1.

6.2 A pneumatic regulator

This pneumatic regulator has also been run as the open loop system. The result is given in figure 6.1. The P band was fixed to 1.8 ^{o}C which corresponds to a P-gain of 0.55 ^{o}C.

6.3 Digital PID regulators

The earlier given P regulator (1), PI regulator (2) and PID regulator (3) have been run through the same test run as the open loop system. The results are given in figure 6.2 and 6.3.

6.4 Regulators based on linear quadratic control theory

The earlier given regulators (7) and (8) have been tested in the same manner as the open loop system. The results are given in figure 6.4.

6.5 A digital onoff regulator

This means that the control signal u(t) will be as follows according to the temperature error signal y(t):

$$u(t) = \begin{cases} 1. & \text{if } y(t) < 0 \\ 0. & \text{if } y(t) \geq 0 \end{cases} \qquad (9)$$

The result is shown in figure 6.2.

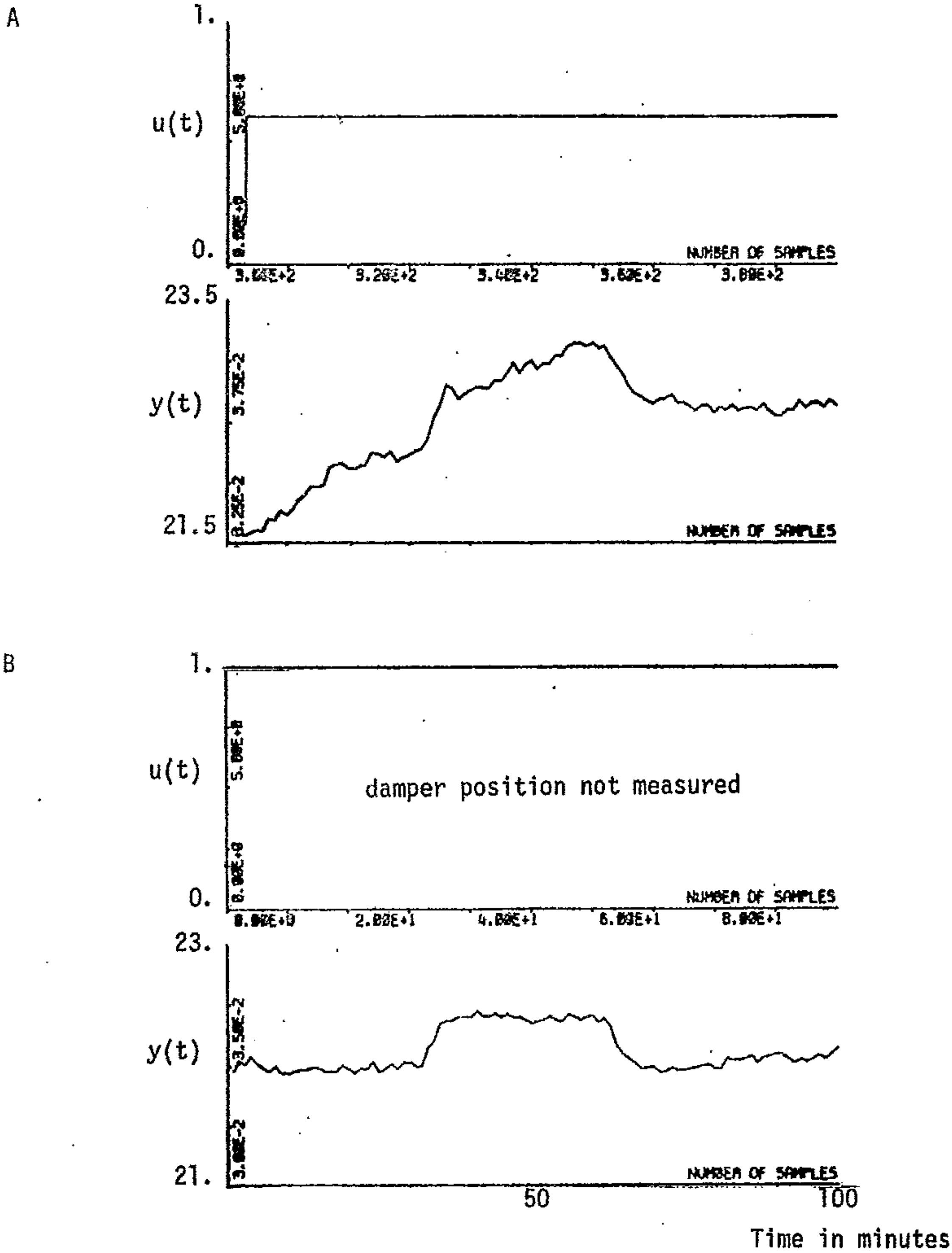

Figure 6.1 Experiments with
A open loop system and
B normal system.
u(t) is the onoff ratio and y(t) is the room air temperature in ^oC

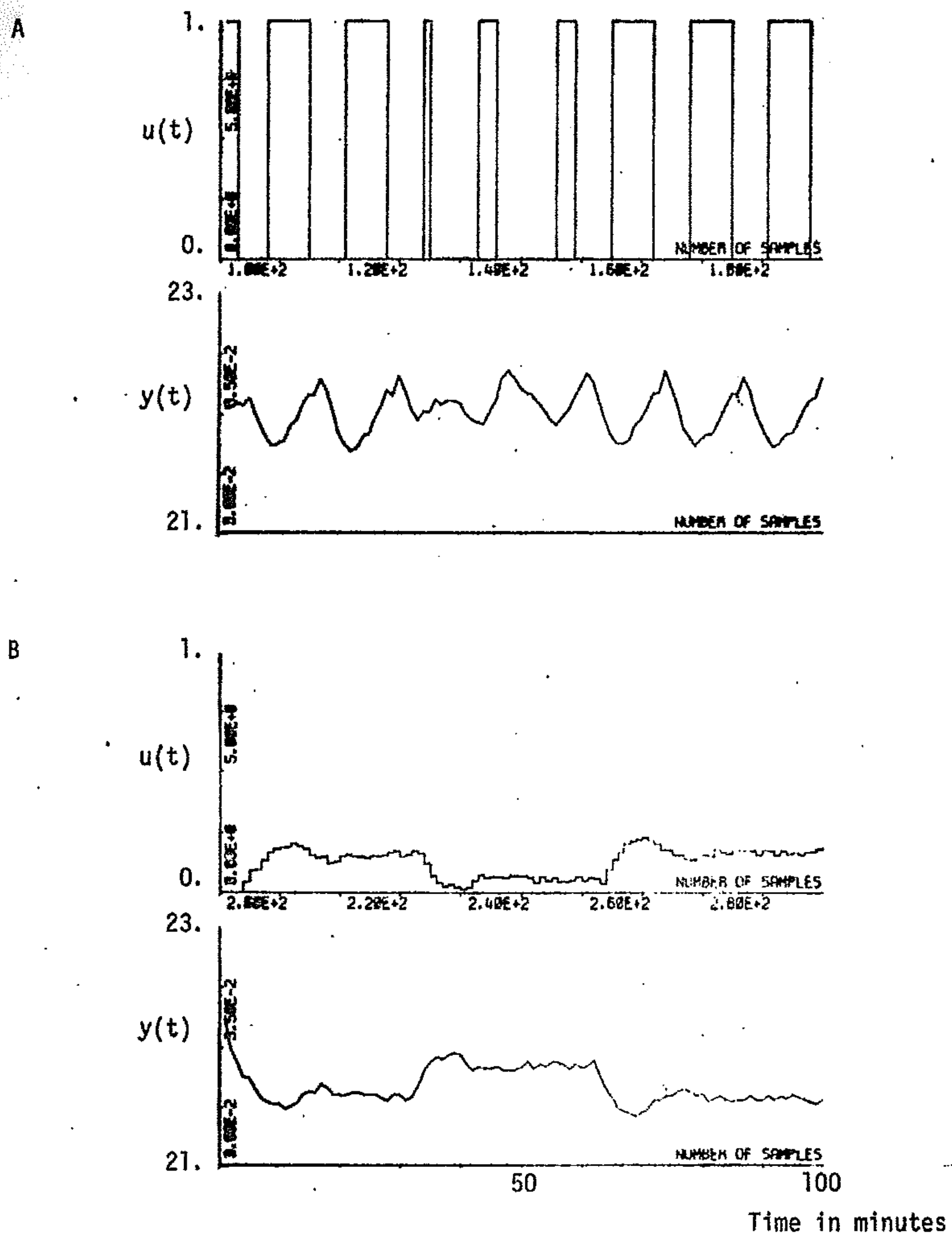

Figure 6.2 Experiments with
A digital onoff regulator (9) and
B digital onoff ratio regulator (1).
u(t) is the onoff ratio and y(t) is the room air temperature in ^{0}C. The setpoint is 22. ^{0}C

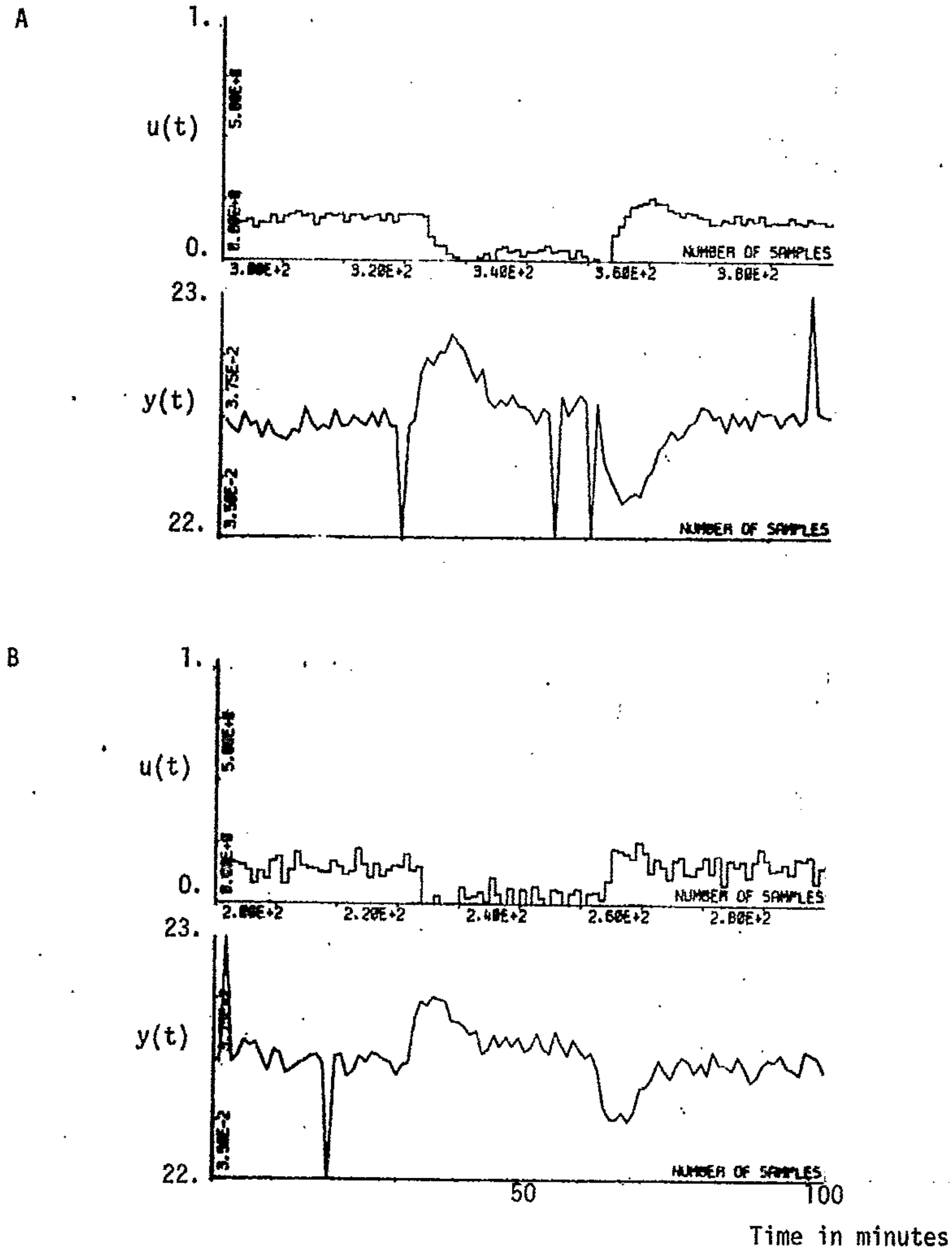

Figure 6.3 Experiments with onoff ratio control with the digital PID regulators A(2) and B(3). u(t) is the onoff ratio and y(t) is the room air temperature in ^{o}C. The setpoint is 22.5 ^{o}C

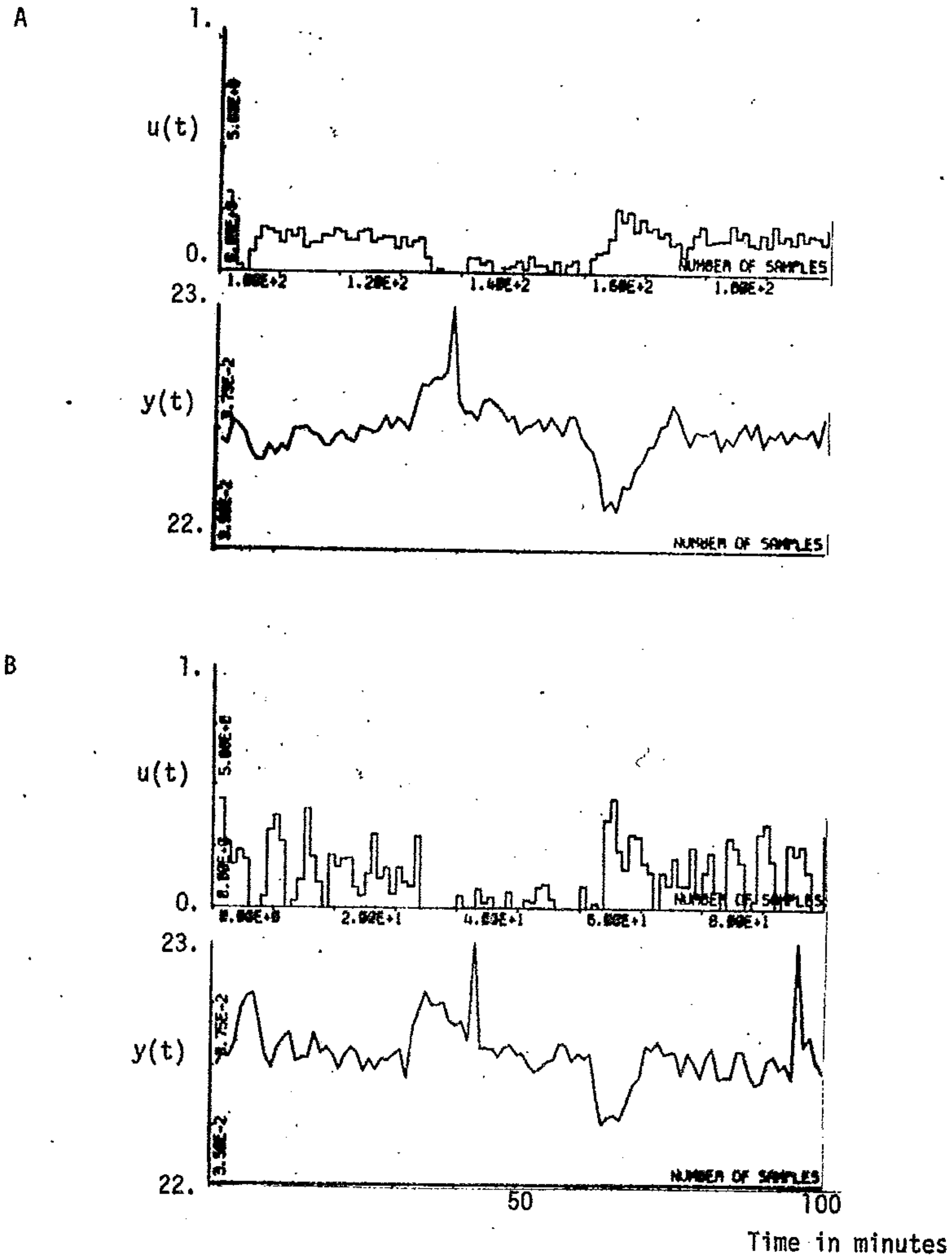

Figure 6.4 Experiments with onoff ratio control with the digital linear quadratic regulators A(7) and B(8). u(t) is the onoff ratio and y(t) is the room air temperature in °C. The setpoint is 22.5 °C.

7 Comparisons of regulators

A simple method to compare the full scale experiments and the simulated has been used. The temperature deviation from the setpoint have been measured in both cases. The ratio between these values and the open loop system value have been calculated. The result is given in table 7.1.

Table 7.1 Comparison between simulated and fullscale control experiments

Regulator	Fullscale experiments		Simulated experiments
	Deviation from setpoint in °C	Normalized to open loop deviation	Normalized to open loop deviation
Open loop	0.52	1.0	1.0
P regulator (1)(peak)	0.36	0.69	0.52
P regulator (1)(level)	0.26	0.50	0.47
PI regulator (2)	0.29	0.55	0.51
PID regulator (3)	0.26	0.50	0.46
LQ regulator (8)	0.32	0.61	0.48
LQ regulator (9)	0.28	0.54	0.42

The figures shows that the model is valuable to use when synthezing regulators or tuning regulators by simulation.

The PID regulator (3) is better than the PI regulator (2). The LQ regulator (9) is better than the LQ regulator (8). The PID regulator (3) should not have been better than the LQ regulator (9).

The model has also been used to compute how digital onoff control would be. The period time was 10 minutes and deviation from the setpoint was 0.4 ^{o}C at 50% load.

The fullscale experiment has a period time of 12.5 minutes and an amplitude of 0.3 ^{o}C. Also these figures shows that the model is useful.

8 Cost analysis

A very crude cost analysis will be made, comparing four different postheater systems. The analysis is based on a building with 150 postheaters. Cost for electric wiring and pneumatic piping have been excluded in the analysis.

8.1 Regulator costs

A. Electromechanical onoff regulator

A thermostat with a smallest difference between on and off of about 1.0 ^{o}C is used. The cost is about 200 kr.

B. Electronic onoff regulator

This regulator has a smallest difference between on and off of about 0.2 ^{o}C. The cost of the sensor is 200 kr and for the regulator 600 kr.

C. Direct Digital Control DDC - with a process computer

Any type of regulator can be implemented. The cost is 300 kr for 1/150 of a process computer, 300 kr for analog input interface and 100 kr for logical output interface. The temperature sensor cost is 200 kr.

D. A pneumatic regulator

The cost for the compressor unit per postheater unit is 70 kr. The sensor cost is 200 kr.

This gives the following regulator (sensor included) costs

A 200 kr
B 800 kr
C 900 kr
D 270 kr

8.2 Postheater cost

The pneumatic postheater system costs 950 kr including dampers and actuator. The postheater with onoff ratio flow control is much simpler. Only a heatexchanger and a magnetic valve is needed. The cost is in this case 300 kr.

8.3 Cooling costs

The costs for the cooling system will differ between the magnetic and the pneumatic system. The undesired temperature raise over the postheater is 1.5 ^{o}C higher when the pneumatic system is used. This will effect both the fixed and operating costs.

The cooling demand can be reduced with 1.5 ^{o}C. The fixed costs for cooling units about 400 000 - 600 000 kcal/h is about 0.30 krh/kcal. The total air flow is 100 000 m^3/h. This will give a reduced fixed cost per postheater unit of 86 kr.

Cooling is assumed to be needed when the outdoor air temperature is higher than 13 ^{o}C for Malmö which is about 30% of the year or 2600 hours (Klimatdataboken). The needed electric effect is 30% of the utilized cooling effect, when cooling units with direct expansion are used. The energy price is 0.09 kr/kWh (high voltage). The difference in operating costs can then be computed to 24 kr/year.

8.4 Summing up and conclusions

The fixed costs are given for alternative A-D in table 8.1. The yearly depreciation has also been computed for a loan over 50 years at a interest of 6%. The estimated temperature accuracy is also given.

Table 8.1 Cost comparison between different postheater systems

Alternative	fixed cost	yearly depreciation 50 years, 6%	control accuracy
A	500 kr	30	±1.0 °C
B	1100 kr	66	±0.5 °C
C	1200 kr	72	±0.2 °C
D	1306 kr	102(78+24)	±1.0 °C

The cheapest alternative is alternative A. The temperature in the room will oscillate with a peak to peak value of about 2 °C. This might in many cases be a sufficient control of the room air temperature.

The inlet air temperature cannot cause any cold air stream down because it will always be 15 °C or more. The preheated air temperature is always 15 ^{o}C.

If the demand of climate comfort is higher then the alternative B seems to be a good solution.

If the alternative C is combined with a total computer control of all climate systems in the building, then this might be the most economic solution.

The preheated air temperature to all the postheater can be chosen after the room with highest cooling demand or according to any other rule. The water temperature to the postheater and the radiator can also be chosen as suitable as possible.

Alarming and error checking can be made by the computer.

The alternative D is the most expensive. The high cost is due to the complicated postheater unit.

The alternatives using the magnetic valve must be implemented very carefully regarding the sound problem, which can be overcome.

The lifetime of the magnetic valve must also be taken into account. Today magnetic valves are garanteed for 10^6 - 10^7 openings and closures. If onoff control is used, with a period time of 12 min, then the lifetime will be about 10-100 years.

9 Remarks and conclusions

The experiences of the experiments can be summarized as follows:

It is very valuable to have a model of the system. It can be used for tuning control parameters by simulation as well as for control law synthesis. The experiments show that a second order model of the process is able to predict the closed loop system very well.

The experiments also showed that digital control could be made better than the normal control. The temperature deviation from the setpoint could be kept less than 0.1 ^{0}C in one point in steady state. However it should be pointed out that the temperature differences between different points in a room can be one or two degrees.

This work shows that it is possible to identify a process, synthese and simulate regulator and finally run the regulator in full scale in less than a week. This is easily done if suitable program packages are available for real time processing, identification and regulator synthesis and simulation are available on the same computer. This work has been carried out in less than two weeks. Delays were caused by an at the start unknown two hours limition of telephone calls, by malfunctioning measurement equipment and by a minor programing error.

The experiments have also demonstrated the possibility of using minicomputers to control air conditioning plants.

In particular, onoff control of a magnetic valve, using pulse length modulated signals may be an attractive way of implementing the control laws on a computer.

The experiments have also shown that a pure onoff control of a postheater is sufficient in many cases.

10 References

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Appendix 1

Used inputs and outputs

Analog inputs

Channel	Sensor	Temperature type
1	1	room air 1
2	2	inlet air
3	7	water to postheater
4	8	air before postheater
5	5	air after postheater
6	6	outdoor air
7	3	room air 2
8	4	room air 3
9	9	water after postheater

Logical inputs none

Analog outputs none

Logical outputs

Number	Controlled object	0/1
0	magnetic valve	closed/open
1	disturbance	off/on
2	not used	
3	damper	normal action/fully opened