Improvement of greenhouse heating control

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Indexing terms: Control equipment and applications, Control systems

Abstract: Improvements to the control of the temperature in greenhouses heated by hot water pipes were developed in order to enhance both energy conservation and crop protection. Acceptable control can be obtained in some greenhouses by feedback of internal air temperature samples only, but much more robust control is obtained if heating pipe temperatures are included in the feedback. The heating system has long time constants, and with digital control the use of a relatively coarse sampling interval leads to better control. Gain coefficients for the feedback can be estimated from analysis of the uncontrolled response to heating if the pole positions for the controlled response are chosen. Suitable pole positions give slightly soft control, and the heating and cooling rates demanded can be achieved with limited adjustments of the heating valve.

1 Introduction

Ways of improving greenhouse heating control were investigated to enhance energy conservation and improve crop protection. Researchers [1–6] have suggested control regimes which can save greenhouse heating energy by reducing the temperature setpoint when heat losses are high (windy, no thermal screen), and increasing it when the losses are lower. To obtain appreciable energy conservation with such regimes, the accuracy of temperature control must be sufficient so that the setpoint can be significantly reduced without any risk that the temperature will fall below an allowed limit anywhere within the crop.

The investigations were carried out in a Venlo greenhouse measuring 13.8 m × 29.0 m, heated using hot water pumped along a 50 mm diameter pipe network with 100 mm diameter fins. The circulation time was about 2 minutes. The oil fired heating system included a heat exchanger to transfer heat from pressurised steam to the hot water pipes, and a valve to regulate the amount of heat supplied to the greenhouse. The environmental computer [7] measured the temperature with a single sensor, and a circulating fan maintained the internal temperature uniform to within 0.75 K. Throughout the first winter the greenhouse was clad with a single layer of glass. Subsequently the glass was lined internally with Melinex plastic film. This double layer gave much higher thermal insulation.

Experimentally estimated parameters of the pipe and internal air temperature transfer functions were used to design a digital controller, and other transfer functions were also used in simulating its response to realistic disturbances. A compromise between close control and moderate valve adjustment appeared to be desirable. This compromise was obtained by the selection of suitable positions in the z plane for the poles in the z transform version of the closed loop transfer function of the controlled system [8].

The digital control algorithm designed gave good control, whereas the performance of the commercial controller used originally varied with the weather and was not consistently good. The algorithm uses a 10 minute sampling and adjustment interval, compared with the 1 minute interval used by the commercial controller. (Some other commercial controllers make adjustments even more frequently [9].) With a digital controller the interval should be long enough to detect a response to the previous adjustment. In the greenhouse, the time constant for transfer of heat from the pipes to the air was 29 min with glass insulation only, and 43 min with the extra insulation. The estimates of the time constant of the response of the pipe temperature to valve adjustments were longer: 52 min for the original greenhouse, and 75 min with the extra insulation. Even with a 10 min sampling interval the differences between successive temperature measurements were very 'noisy', and control valve adjustments were reduced as a result of filtering the measurements.

It is very difficult to demonstrate the relative merits of different control algorithms, or of using a particular algorithm with different gain factors, in a single greenhouse. The behaviour of any controller depends strongly on external conditions which are impossible to control and rarely similar on different occasions. Experiments to compare algorithms should be conducted with an array of identical greenhouses; however, only one Venlo greenhouse was available. In this investigation computer simulations have been used to predict the expected behaviour of the digital algorithms with different control gains and different gains in the filter of the temperature measurements. Experiments in a single greenhouse demonstrated superior control with the new digital algorithm and reduction in valve movement obtained from filtering the temperature measurements.

2 Measurement and analysis of open loop responses of the heating system

Experiments were devised to measure the open loop responses of the greenhouse heating pipe and internal air

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temperatures to changes in heating valve aperture. Measurements of other influences on these temperatures, such as solar radiation, were also recorded. Time series analysis of the data revealed transfer functions relating changes in the temperatures to changes in the measured inputs. The influence of random disturbances, of unknown origin, on the measured temperature variations was also revealed by the analysis.

A computer made pseudorandom decisions at hourly intervals to shut the heating valve or open it by a prescribed amount. Hourly intervals were chosen because of the slow responses of the measured temperatures. For the same reason a course sampling interval of 10 minutes was chosen between measurements. With this interval most of the changes in internal air temperature between samples were statistically significant, but would not have been with a much shorter interval. The effects of changes in valve aperture were usually most apparent in data recorded at night, because of the absence of solar radiation. Initially only night-time data were analysed. However, at a later date, all the items in Table 1 were recorded over consecutive days and nights for subsequent analysis.

Table 1: Items recorded for analyses of input-output relationships

No. Item	No. Item
1 fractional aperture of the value	4 external temperature, °C
	5 wind speed, m/s
2 heating pipe temperature, °C	6 internal air temperature, °C
3 external radiation intensity, W/m²	

The effects of changes in each of the measured inputs on the pipe and internal air temperatures were analysed using a multiple input version of the refined instrumental variable method [10]. In this method an instrumental variable is an estimate of the noise free component of the output arising from an input variable, and a separate transfer function is associated with each such variable. Iterative improvements to the estimates of the parameters of the transfer functions are obtained, using filtered input and output variables, which lead to maximum likelihood estimates eventually in the refined method. The analyses fitted equations of the following form:

$$y_k = \sum_i x_{ik} + n_k \tag{1}$$

where

$$x_{ik} + a_{i1} x_{ik-1} = b_{i0} u_{ik} \quad \text{and} \quad n_k + c_1 n_{k-1} + c_2 n_{k-2} = e_k$$

and

k = the number of a sampling instant
i = an item number as defined in Table 1
y_k = sample k of an output (i.e. temperature) less the average output
x_{ik} = sample k of the instrumental variable related to input i of Table 1
u_{ik} = the kth sample of the deviation of input i from its average value
n_k = the total disturbance of unknown origin affecting the output y_k
e_k = the kth random or 'white noise' disturbance of unknown origin
a_{i1}, b_{i0}, c_1 and c_2 are parameters which are estimated from the data.

Incidentally, time constants τ_i are related to the parameters a_{i1}:

$$\tau_i = \frac{-\Delta t}{\ln(-a_{i1})} \tag{2}$$

Δt is the 10 minute sampling interval.

The heating pipe temperature variations were generally much larger than those of the internal air temperature, and so it was possible to disregard the internal air temperature variations when analysing the pipe temperature variations.

2.1 Open loop response of the single glass greenhouse

Fig. 1 shows some open loop temperature responses to valve adjustments in the greenhouse. Each of the step changes in valve aperture occurred immediately after sampling that aperture. Table 2 shows the results of the analysis of the heating pipe temperatures. The only input which had a statistically significant effect was the fractional valve aperture, which accounted for 97% of the variance of the pipe temperatures. Therefore only four parameter estimates are shown in the table. The estimate of the standard deviation of e_k is 0.16 K.

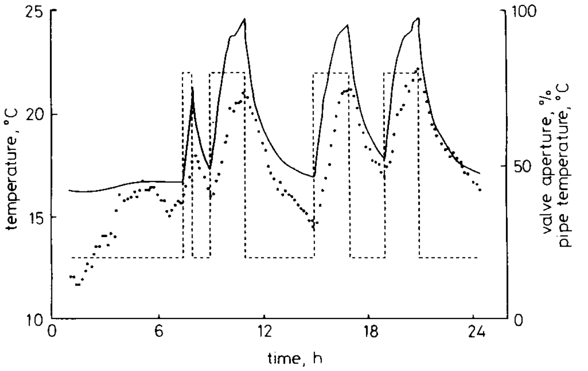

Fig. 1 *Open loop control in Venlo greenhouse, 19th December 1985*
······· air temperature
——— pipe temperature
------- valve aperture

Table 2: Parameter estimates obtained from heating pipe temperature data for 10th December 1985 relating it to valve apertures and random disturbances

Parameter	a_{11}	b_{10}	c_1	c_2
Estimated value	−0.8258	17.85 K	−1.1892	0.3009
Standard error	0.0065	0.039 K	0.0971	0.0845

The data were also analysed to estimate the relationship between pipe temperature and internal air temperature. The internal air temperature was also found to depend on the external air temperature. 97% of the variance of the internal air temperature was accounted for by these two inputs, i.e. items 2 and 4 of Table 1. Five statistically significant parameters were found and their estimates are shown in Table 3. The corresponding estimate of the standard deviation of e_k is 0.23 K.

The overall model presented in Tables 2 and 3 is that of a second order system, but it was found that a first order transfer function could also be closely fitted to the relationship between valve aperture and internal air temperature. Presumably this is because the time constant for transfer of heat from the pipe to the air, namely 29

Table 3: Parameters obtained from greenhouse temperature data for 10th December 1985 relating it to pipe and external air temperatures and random disturbance

Parameter	a_{21}	b_{20}	a_{41}	b_{40}	c_1
Estimated value	−0.7058	0.0360	−0.9529	0.0309	−0.7127
Standard error	0.0209	0.0022	0.0190	0.0084	0.0722

minutes, is only three sampling intervals long and, moreover, short compared to the sum of the two time constants of the system.

2.2 Open loop response of the Melinex-lined greenhouse

A second order system was necessary to model the response of the internal air temperature to changes in volve aperture in the insulated greenhouse.

Greenhouse heating data were collected at 10 minute intervals from the 13th to 18th January 1987. Fig. 2 shows part of this data. The recorded solar radiation data were found to be unreliable, but the intensity was so low that it had only a slight effect on the greenhouse temperature. Tables 4 and 5 show the values of the parameters estimated from the data for the other variables.

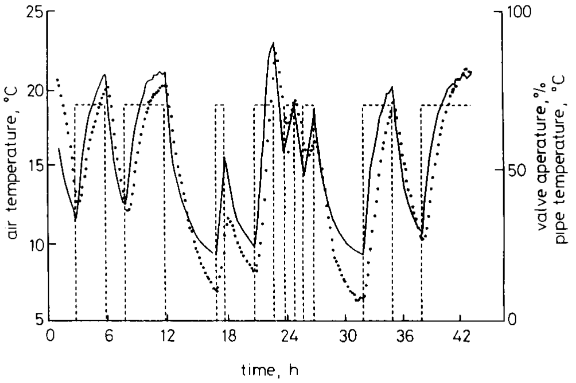

Fig. 2 *Open loop control in Venlo greenhouse, 13th–14th January 1987*

······· air temperature
——— pipe temperature
------- valve aperture

Table 4: Parameters fitted to the pipe temperature data for the 13th–18th January 1987, relating it to valve aperture and random disturbances

Parameter	a_{11}	b_{10}	c_1	c_2
Estimated value	−0.8755	10.579	−1.3685	0.3851
Standard error	0.0032	0.0105	0.0355	0.0355

Table 5: Parameter estimates from an analysis of greenhouse temperatures for 13th–18th January 1987

Parameter	a_{21}	b_{20}	a_{41}	b_{40}
Estimated value	−0.7925	0.0540	−0.781	0.182
Standard error	0.0049	0.0010	0.069	0.053
Parameter	a_{51}	b_{50}	c_1	c_2
Estimated value	−0.982	−0.015	−1.2209	0.2384
Standard error	0.008	0.006	0.0377	0.0376

The pipe temperature variations were modelled with one input which explained 93% to 94% of its variance, namely the fractional valve aperture. Table 4 lists the parameters in the fit to the pipe temperatures. The estimate of the standard deviation of e_k is 0.61 K.

The internal air temperature was modelled from three inputs, each with a first order transfer function, and the inputs were the pipe temperature, external temperature and wind speed, omitting solar radiation. These inputs explained 92% of the variance of the internal air temperature. With the two parameters of the noise model included there were eight statistically significant parameters. The parameter estimates are shown in Table 5, and the estimated standard deviation of e_k is 0.15 K.

3 Development and simulation of the final control algorithm

The analyses, described above, of the open loop response of the greenhouse indicated the sort of controller required. Data from these analyses were also used in simulating the performance of a controller in order to choose suitable gain coefficients or, alternatively, closed loop pole positions. Whereas the response of the uninsulated glass greenhouse can be approximated by a first order transfer function, and simpler algorithms sufficed for its control, a second order transfer function is required to represent the Melinex-lined greenhouse, and the final control algorithm is more complicated.

If the integral of internal air temperatures is artificially introduced as a state variable, then its control can be automatically included in state variable feedback [11]. Two variables for feedback can naturally be specified for a second order system, and in this case the appropriate variables are pipe temperature and internal air temperature, but, with the addition of the integral control, three feedback gain coefficients have to be chosen. An alternative to choosing the gain directly is to specify instead the positions of the three poles of the closed loop system in the z plane. An advantage of the latter procedure is that the stability and degree of control can be pictured in terms of the positions of the poles [8].

Measurements of external inputs such as external temperature could be utilised in the estimation of control action, but such sophistication does not appear to be necessary. The temperature drifts caused by the external inputs were corrected sufficiently promptly by the integral component of the feedback. Incidentally, control of the temperature in the uninsulated glass greenhouse with online parameter estimation, similar to that used earlier in controlling ventilation [12], led to less precise control than the use of fixed gain coefficients including an integral gain factor.

The feedback control is described by the following equation:

$$u_{k+1} - u_k = -K_{PP}(y_{Pk} - y_{Pk-1}) - K_{PA}(x_{Ak} - x_{Ak-1}) - K_I(R_{k+m} - y_{Ak}) \qquad (3)$$

where

u_k = the fractional aperture of the heating valve at sampling instant k
y_{Pk} = the heating pipe temperature at sampling instant k
y_{Ak} = the internal air temperature at sampling instant k
x_{AK} = either y_{Ak} or a filtered version of it
R_{k+m} = the anticipated setpoint at sampling instant $k+m$
K_{PP}, K_{PA} and K_I are the gain coefficients to be selected.

Fig. 3 depicts the whole controller schematically. The internal air temperature is kept close to a setpoint which is either constant or varies linearly. To avoid a delay in following the setpoint, the internal air temperature is compared with an anticipated value of the setpoint at m sampling intervals ahead. The control action immediately follows receipt of the temperature samples, although the resultant valve aperture is numbered with the next sampling instant.

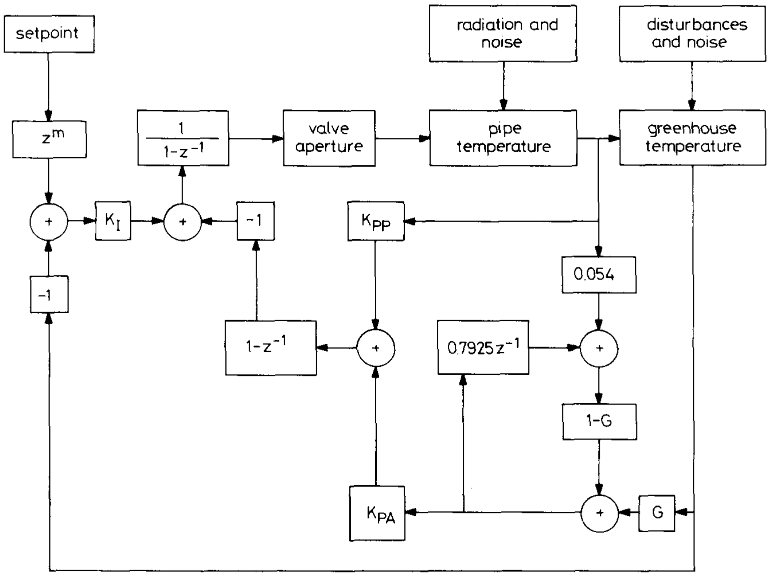

Fig. 3 *Greenhouse temperature controller*

The additional gain coefficient G in Fig. 3 does not influence the estimated positions of the closed loop poles of the system, but it influences the way in which the controller responds to noise disturbances in the measured internal air temperature. G can be set to any value above 0.0 but not greater than 1.0, but $G = 1.0$ would be preferable for the first sampling interval. If G is less than 1.0 the proportional feedback of the greenhouse air temperature is diminished by the factor G, but it is supplemented by a proportion $1 - G$ of a less noisy predicted value of the air temperature. The predictions are made from the pipe temperature using the estimate of the transfer function between the pipe and air temperatures. This procedure can considerably reduce unnecessary valve movements arising from noise in the feedback while having little effect on the temperature control. A convenient measure of valve movement is the percentage of full aperture traversed per hour.

The proportional and integral gain coefficients can be calculated from the desired pole positions of the closed loop system with the parameter estimates in Tables 4 and 5. Suitable pole positions are those for which the valve adjustments are neither excessive nor too sluggish. If too much control is demanded the valve may alternate between shut and fully open, but if too little control is demanded the controller will be slow to correct for temperature drifts. The delay in following the anticipated values of the setpoint is a good indicator of how quickly temperature drifts can be corrected. An algebraic expression was readily derived for the asymptotic delay in following a ramp change in the setpoint, and this enabled the delay to be plotted as a function of the pole positions. Fig. 4 shows contours of equal delay or look ahead compensation in following a setpoint ramp when all the poles are at a radius R in the z plane and at angles θ, zero and $-\theta$. If $R = 0.5$ and $\theta = 30°$ the look ahead is 30 minutes, and acceptable control is obtained. For this set of pole positions, $K_{PA} = 0.662$, $K_{PP} = 0.66$, and $K_I = 0.330$.

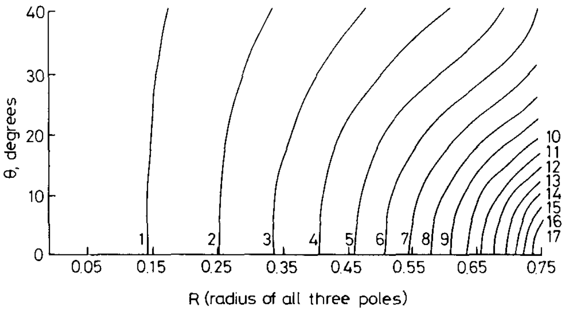

Fig. 4 *Delays in response to a temperature ramp*
Contours at 15, 20, 25 minutes, etc.

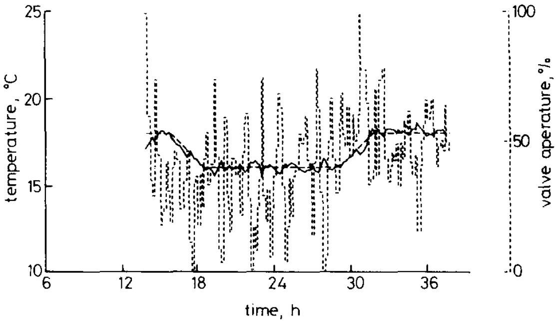

Fig. 5 *Simulated control with $G = 1$ and external disturbances as for 13th–14th January 1987*
$K_{PP} = 0.066$, $K_{PA} = 0.663$, $K_I = 0.330$
——— air ------- valve
- - - - set point

Figs. 5–7 show simulations of the performance of the control algorithm with the well insulated greenhouse and the external disturbances recorded on 13th–14th January 1987. The day time setpoint was 18°C and at night it was 16°C. Fig. 5 resulted from placing the poles at the radius $R = 0.5$ with $\theta = 30°$ and choosing $G = 1$. The root mean square temperature deviation over the simulated portion is 0.22 K. In Fig. 6 the control would have been the same, but the gain coefficients were deliberately calculated for the wrong version of the greenhouse, yet the performance of the controller is acceptable. In Fig. 7 the gain coefficients, other than G, are the same as in Fig. 5. With $G = 0.4$, instead of 1.0, the filtering of the feedback has resulted in a reduction in the sum of the absolute values of the valve movements from 106% to 73% of full aperture per hour with only an increase in root mean square temperature deviation from the setpoint, from 0.22 to 0.24 K.

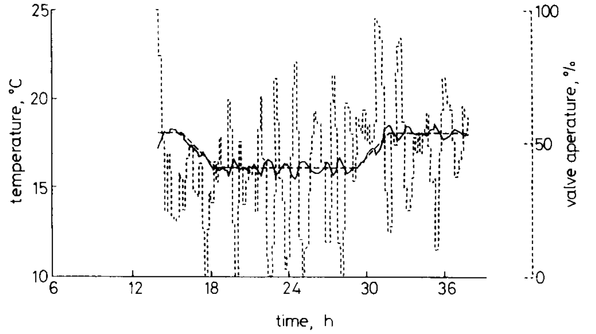

Fig. 6 *Simulated control with $G = 1$*

Gains as for the wrong greenhouse
$K_{PP} = 0.036$, $K_{PA} = 0.506$, $K_I = 0.300$
——— air ------- valve
– – – – setpoint

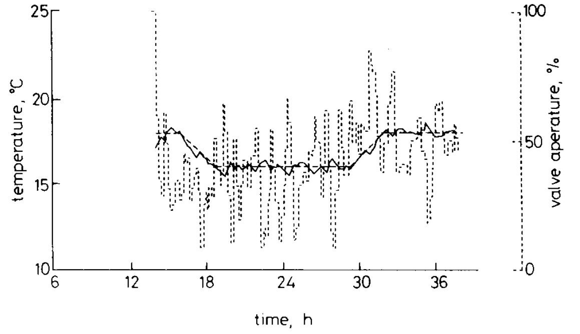

Fig. 7 *Simulated control with $G = 0.4$ and external disturbances as for 13th–14th January 1987*

$K_{PP} = 0.066$, $K_{PA} = 0.663$, $K_I = 0.330$
——— air ------- valve
– – – – setpoint

4 Experimental results with the controller

The final algorithm was used to control the air temperature of the Melinex-lined greenhouse throughout a full heating season. Fig. 8 shows the control achieved on 19th January 1988. $G = 0.4$ and the setpoint was anticipated with a lead time of 30 minutes. Including the dawn and dusk ramps, the desired mean temperature was achieved within 0.01 K. The root mean square error was 0.16 K and the maximum error including the ramps (sunset to sunrise) was 0.4 K.

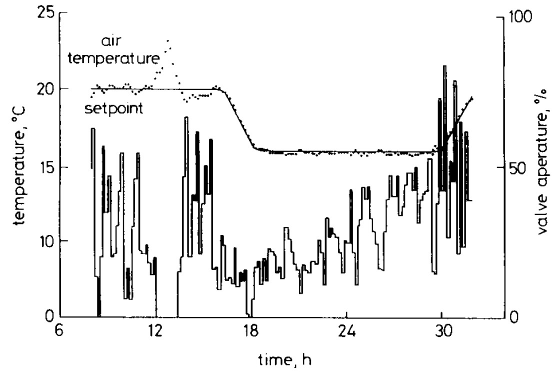

Fig. 8 *Digital heating control on 18th January 1988*
$K_{PP} = 0.066$, $K_{PA} = 0.662$, $K_I = 0.330$, $G = 0.4$

The greenhouse measurements demonstrated the reduction in valve movement which could be obtained from filtering the air temperature measurements. For example, Fig. 9 show the measurements obtained overnight on 4th December 1988. Before midnight $G = 1.0$ with 113% valve movement per hour. After midnight $G = 0.4$ with 84% valve movement per hour — a reduction of 26%. However, the reduction was not always so obvious, and a series of measurements was required to demonstrate the reduction in valve movement. A single measurement was obtained each night of the average valve movement per hour between sunset + 2 hours and sunrise −2 hours, when the air temperature setpoint was constant; i.e. excluding the dawn and dusk ramps. With any algorithm tested with a particular set of gain factors, there was a 4 to 1 variation in valve movement, probably due to differences in external conditions on different nights and within a particular night. The main influences were thought to be wind speed and external temperature but consideration only of these left many observations unexplained. Table 6 shows some of the measurements obtained and includes several examples of different valve movement in apparently similar conditions (27th December and 4th February; 14th January and 25th January).

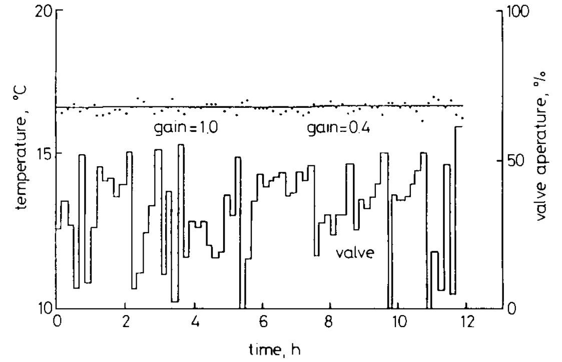

Fig. 9 *Valve movements with $G = 1.0$ and $G = 0.4$, 4th December 1987*

······ air temperature
——— setpoint

The benefit of filtering could be demonstrated by plotting the average valve movement/hour against pipe temperature as the movement seemed to be an indicator of how hard the heating system had to work in the presence of the various external influences. Fig. 10 shows the valve movement per hour plotted against pipe temperature for the final algorithm with $G = 1.0$ and $G = 0.4$, and it also includes observations with the commercial algorithm from the previous year's heating season. The valve movement increases with increasing pipe temperature for all the algorithms. The movement with the final algorithm with $G = 1.0$ is less than with the commercial algorithm. There is a further reduction when $G = 0.4$. The percentage reduction depends on the pipe temperature. When the pipe temperature is 40°C, the reduction with $G = 0.4$ is about 30%.

Table 6 shows that the algorithm correctly achieves the required mean temperature overnight usually with an

Table 6: Performance of the final control algorithm

No filtering of the air temperatures ($G = 1$)

Date	Lift, K	Wind, m/s	Error, K			Pipe, K		Valve, %	
			mean	RMS	max	mean	RMS	mean	move/hr
16th Dec.	13.7	4.50	0.21	0.21	0.6	58.3	3.2	32.8	191
18th Dec.	16.8	3.18	0.02	0.24	0.7	61.6	4.2	34.5	197
20th Dec.	13.5	3.29	0.05	0.22	0.6	51.9	3.1	31.8	174
22nd Dec.	15.0	0.99	0.08	0.28	1.0	43.7	3.7	25.8	143
24th Dec.	10.8	2.33	−0.03	0.24	0.6	42.6	4.7	22.4	125
26th Dec.	11.4	3.34	0.01	0.26	0.8	50.2	4.2	25.5	142
28th Dec.	12.8	5.51	0.02	0.21	0.6	57.5	3.5	30.3	176
30th Dec.	14.1	4.45	0.01	0.27	1.0	59.5	4.5	35.5	201
02nd Jan.	16.1	7.20	0.04	0.23	0.7	64.6	3.3	30.7	177
08th Jan.	6.3	2.77	0.05	0.12	0.4	28.7	3.0	12.3	69
14th Jan.	10.8	1.09	0.06	0.20	0.6	36.0	3.5	17.6	92
18th Jan.	9.6	2.63	0.03	0.16	0.5	33.5	1.9	12.3	68
20th Jan.	14.5	1.50	−0.01	0.12	0.3	46.5	2.9	15.2	84
23rd Jan.	6.2	2.75	0.03	0.16	0.7	27.6	1.6	9.4	52
25th Jan.	10.3	1.03	−0.01	0.16	0.5	34.6	2.6	11.8	61
28th Jan.	8.9	2.49	−0.00	0.13	0.3	34.0	2.2	11.0	61

Air temperature filtered ($G = 0.4$)

Date	Lift, K	Wind, m/s	Error, K			Pipe, K		Valve, %	
			mean	RMS	max	mean	RMS	mean	move/hr
15th Dec	10.9	2.1	0.00	0.17	0.4	38.5	2.8	12.3	71
17th Dec.	10.9	4.8	−0.01	0.18	0.5	52.3	2.6	22.9	136
19th Dec.	13.8	5.7	0.03	0.18	0.5	54.8	2.7	27.2	163
21st Dec.	14.6	2.8	−0.04	0.31	0.9	58.8	6.8	22.2	129
23rd Dec.	13.9	1.2	−0.02	0.16	0.5	39.4	1.7	9.2	53
25th Dec.	13.9	2.0	0.04	0.21	0.6	50.1	3.8	21.0	124
27th Dec.	11.29	4.5	0.02	0.29	1.0	55.5	3.7	28.0	162
29th Dec.	14.5	3.9	−0.05	0.27	1.2	61.5	5.9	28.1	164
31st Dec.	16.4	4.9	0.04	0.29	1.0	62.8	3.8	33.3	192
03rd Jan.	15.8	3.9	0.03	0.29	1.0	57.5	3.7	28.3	164
05th Jan.	7.5	3.4	0.04	0.31	0.9	31.0	4.0	11.6	63
12th Jan.	10.6	4.4	0.04	0.24	1.0	42.6	3.4	20.1	113
13th Jan.	10.5	1.4	−0.08	0.15	0.6	37.4	4.7	11.2	62
15th Jan.	15.0	0.5	−0.04	0.19	0.7	40.5	2.9	16.7	97
17th Jan.	11.9	1.8	−0.02	0.27	0.9	37.7	2.8	12.2	70
19th Jan.	9.3	1.8	−0.05	0.12	0.4	34.4	3.6	7.6	42
22nd Jan.	15.2	2.6	−0.03	0.12	0.6	48.3	2.3	17.6	103
24th Jan.	9.7	1.4	−0.04	0.16	0.9	34.7	1.4	5.6	31
26th Jan.	12.6	0.4	−0.08	0.23	0.8	37.8	3.9	7.9	45
27th Jan.	12.4	2.9	−0.05	0.16	0.6	41.3	2.7	12.3	70
01st Feb.	8.9	6.9	−0.04	0.21	1.0	40.2	1.9	7.9	46

$K_{PA} = 0.662$, $K_{PP} = 0.066$, $K_I = 0.33$

error of under 0.05 K. The average overnight root mean square error in maintaining the temperature was 0.39 K for 18 nights with the commercial algorithm, and 0.20 K for the tests with the final algorithm with $G = 1.0$ or 0.4. It can be seen from Table 6 that with the final algorithm the root mean square error was never as high on any night as the average root mean square error with the commercial algorithm, and this fact indicates that the improvement with the new algorithm is statistically significant. The root mean square errors were probably not dependent on pipe temperatures. Even with these low root mean square errors the maximum error in the controlled temperature could be 1.0 K, and with possible temperature variations within the greenhouse, there could be larger local temperature errors. The commercial controller was used with a gain of 10 and integral action time of 20 minutes. Possibly it could have been tuned better, but optimum tuning is one of the problems with these algorithms, when the performance can vary so much from one night to another.

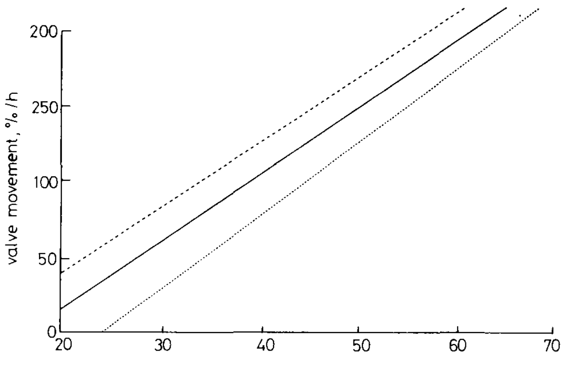

Fig. 10 *Analysis of 1987/1988 valve movements*

—— $G = 1.0$
······· $G = 0.4$
– – – – commercial

5 Conclusions

The addition of feedback of heating pipe temperatures to proportional and integral feedback of internal air temperatures resulted in much more robust control by the new algorithm finally developed. The control algorithms developed earlier in the investigations did not have feedback of pipe temperatures, and these were found to be only suitable for the uninsulated greenhouse. The final algorithm, developed for the Melinex-lined greenhouse, also worked well with the uninsulated greenhouse. Changes to its gain coefficients on changing the insulation of the greenhouse were helpful to temperature control but not essential for acceptable control.

The new algorithm, which has a much longer interval between measurements, has given results consistently superior to the commercial algorithm.

Greenhouse experiments demonstrated the effectiveness of filtering the greenhouse temperature measurements to reduce the valve movement. The small loss of accuracy expected could not be detected in the measurements. A special feature of the filter is its use of the prediction of greenhouse air temperatures from heating pipe temperatures. The percentage reduction in valve movement depended on the pipe temperature required to achieve the setpoint. The pipe temperature depended on external influences which varied from night to night. Consequently the results took several months to obtain, and demonstrate the difficulty of carrying out such investigations in a single greenhouse.

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7 References

1 SAFFELL, R.A., and MARSHALL, B.: 'Computer control of air temperature in a glasshouse', *J. Agric. Ang. Res.*, 1983, **28**, pp. 469–478

2 HURD, R.D., and GRAVES, C.J.: 'The influence of different temperature patterns having the same integral on the earliness and yield of tomatoes', *Acta Horticulturae*, 1984, **148**, pp. 547–554

3 BAILEY, B.J.: 'Wind dependent control of greenhouse temperature', *Acta Horticulturae*, 1985, **174**, pp. 381–286

4 LANGHANS, R.W., WOLFE, M., and ALBRIGHT, L.D.: 'Use of average night temperatures for plant growth for potential energy savings', *Acta Horticulturae*, 1985, **115**, pp. 31–36

5 MILLER, W.B., LANGHANS, R.W., and ALBRIGHT, L.D.: 'Plant growth under averaged day/night temperatures', *Acta Horticulturae*, 1985, **174**, pp. 313–320

6 HENDRIKS, L.: 'Neue Gewächshaus-Technik bedingt neue Regelstrategien', *Gärtnerbörse und Gartenwelt*, 1987, **24**, pp. 872–879

7 HOOPER, A.W.: 'Computer control of the environment in greenhouses', *Comput. Electron. Agric.*, 1988, **3**, pp. 11–27

8 FRANKLIN, G.F., and POWELL, J.D.: 'Digital control of dynamic systems' (Addison-Wesley, London, 1980)

9 SANGER, T.R., 'Measurement and control of temperature, humidity and carbon dioxide concentration in greenhouses'. Royal Agricultural Society of England, Monograph Series No. 4, *Farm Electron. Comp.*, 1985, pp. 269–287

10 JAKEMAN, A.J., STEELE, L.P., and YOUNG, P.C.: 'Instrumental variable algorithms for multiple input systems described by multiple transfer functions', *IEEE Trans.*, 1980, **SMC-10**, pp. 593–602

11 YOUNG, P.C., and WILLEMS, J.C.: 'An approach to the linear servomechanism problem', *Int. J. Control*, 1972, **15**, (5), pp. 961–979

12 DAVIS, P.F.: 'A technique of adaptive control of the temperature in a greenhouse using ventilator adjustments', *J. Agric. Eng. Res.*, 1984, **29**, pp. 241–248