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ACCURATE AND ENERGY CONSERVATIVE GROWTH CHAMBER WITH TIME DIVISION PID CONTROL ACTION

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EGUCHI H., TOH K., KITANO M. and MATSUI T. *Accurate and energy conservative growth chamber with time division PID control action.* BIOTRONICS **14**, 15–31, 1985. The time division PID control action was applied to air temperature and humidity control in a growth chamber where four direct-expansion coils were used for cooling and dehumidifying. This system was optimalized by adjusting the control interval of the time division PID control action: The interval of 60 sec was optimal for accurate control and energy conservation. In this growth chamber, it was made possible to control air temperature and humidity with accuracies of ± 0.3°C and ± 3 %RH even under energy conservative condition.

INTRODUCTION

For environment control, accuracy and energy conservation to economize the running cost are important problems. In general, accurate control and energy conservation are antinomic to each other in phytotron and growth chamber. In accurate control, the brine coil is usually used for cooling and dehumidifying, as the volume of circulated brine can be manipulated continuously through motor valve by PID control action (*2*). This system, however, is large-sized and complicated with many elements. On the other hand, direct-expansion coil is useful as a compact and simple element, but this must be manipulated by on-off control action of refrigerators and results in cycling of controlled variables. Furthermore, it is impossible to repeat startup and shutdown of the refrigerator at frequent intervals for preventing the compressor damage caused by floodback and flooded start (*1*). These functional disadvantages to on-off action of refrigerator make it difficult to control air temperature and humidity accurately. Therefore, in highly accurate control by using direct-expansion coil, refrigerator is continuously operated, where heating and humidifying loads are kept almost constant at all times (*4*). But this system is not reasonable for energy conservation. For plant research, it is necessary to develop new control system satisfying both problems. The present paper

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deals with accurate and energy conservative control with time division PID control action in a growth chamber.

CONTROL SYSTEM

Schematic diagram of control system is shown in Fig. 1. The controlled environment room (CR) of the growth chamber was 1.5 m (width) $\times$ 1.0 m (depth) $\times$ 1.0 m (height), in which controlled air flowed out laterally with a velocity of about 0.3 m sec^{-1}. Controlled variables (PV_t) of air temperature and humidity were detected in a return air chamber by ventilated psychrometer (TH) of Pt 100 Ω (R220-10, CHINO WORKS, LTD.) (*3*). The signals of controlled variables were transmitted to the controller (CPU) through converter (CONV) and interface at a given sampling interval (Δt). Controlled elements consisted of four direct-

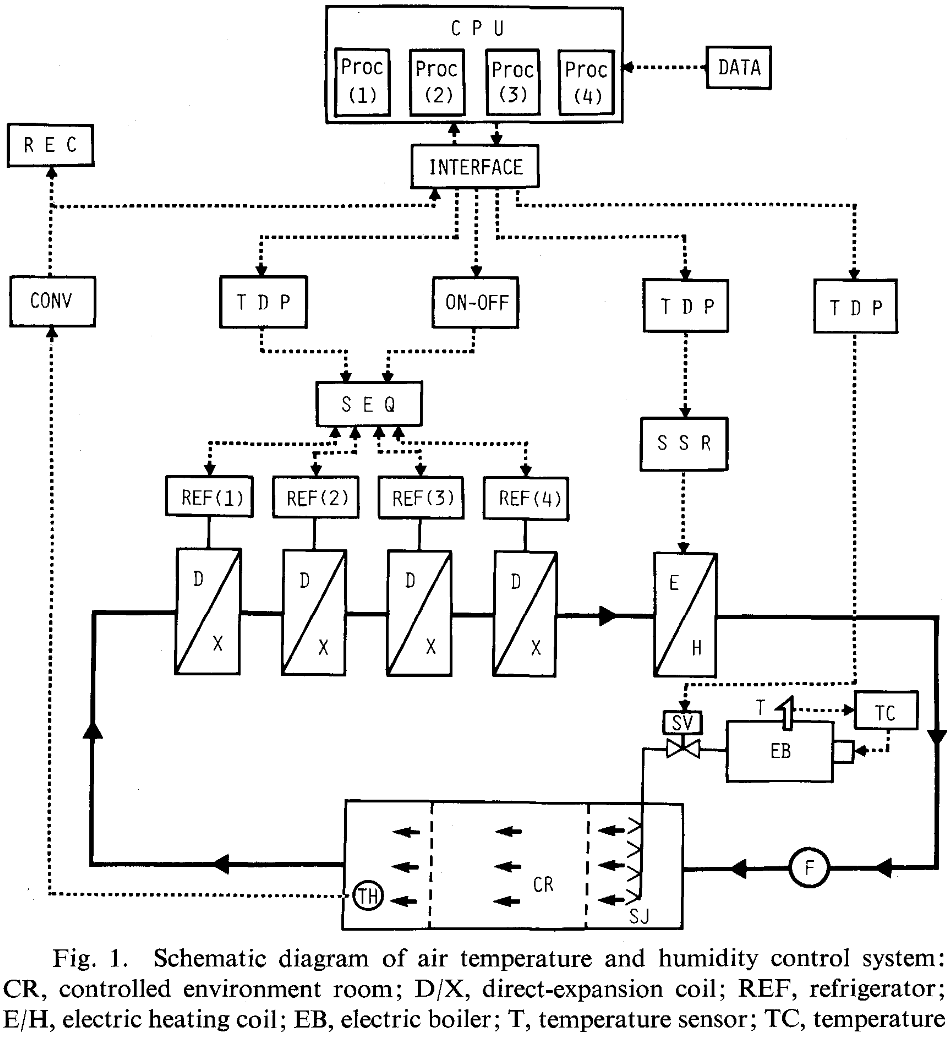

Fig. 1. Schematic diagram of air temperature and humidity control system: CR, controlled environment room; D/X, direct-expansion coil; REF, refrigerator; E/H, electric heating coil; EB, electric boiler; T, temperature sensor; TC, temperature controller; SV, solenoid valve; SJ, steam jet; F, fan; CPU, controller; Proc, digital computer; TDP, time division positioner; ON-OFF, two-value controller; SEQ, sequence controller; SSR, non-contact relay; TH, ventilated psychorometer; CONV, converter; REC, recorder.

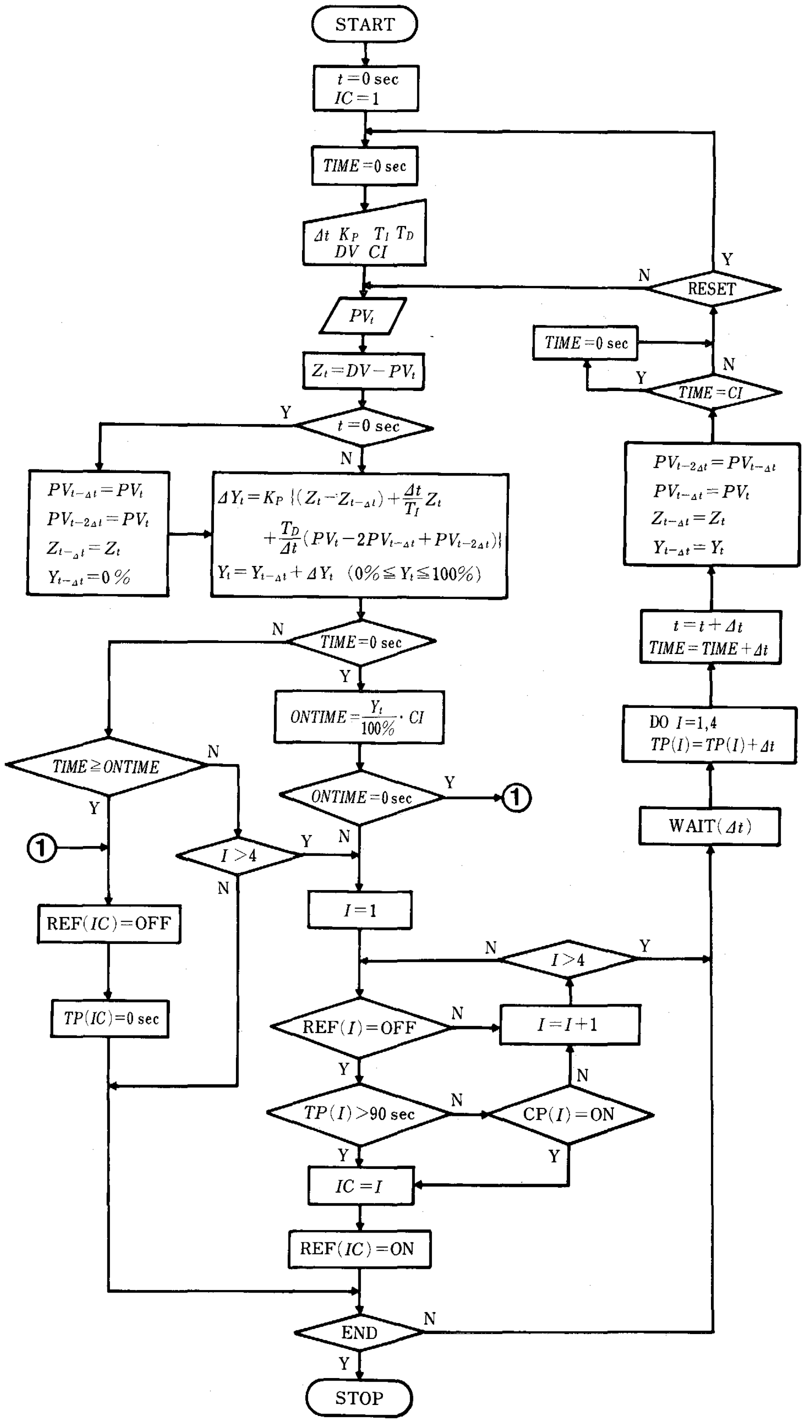

Fig. 2. Flow chart for cooling: t, time; *TIME*, elapsed time from the start of a control interval; Δt, sampling interval; K_P, proportional gain; T_I, reset time; T_D, rate time; DV, desired value; CI, control interval; PV_t, controlled variable; Z_t, controlled deviation; Y_t, manipulated variable; REF, refrigerator; IC, selected REF for cooling; CP, compressor of REF, *ONTIME*, operating time of REF in a control interval; *TP*, elapsed time in REF after receiving "OFF" signal.

expansion coils (D/X; 6 rows × 15 columns × 450 mm in length) for cooling and dehumidifying, an electric heating coil (E/H; 2 rows × 11 columns × 450 mm in length, 8 kW) and an electric boiler (EB; 8 kW) for humidifying. The four direct-expansion coils were connected with respective four refrigerators (REF; 1.5 kW). The controller (CPU) was composed of four digital computers (Proc; DC-7334-00-SP, CHINO WORKS, LTD.) corresponding to cooling, dehumidifying, heating and humidifying. Each manipulated variable was calculated in the respective controllers as follows,

$$Y_t = Y_{t-\Delta t} + K_p\left\{(Z_t - Z_{t-\Delta t}) + \frac{\Delta t}{T_I} Z_t + \frac{T_D}{\Delta t}(PV_t - 2PV_{t-\Delta t} + PV_{t-2\Delta t})\right\} \tag{1}$$

where: Y_t, manipulated variable ($0\% \leqq Y_t \leqq 100\%$); K_p, proportional gain ($K_p > 0$ in heating and humidifying, and $K_p < 0$ in cooling and dehumidifying); T_I, reset time; T_D, rate time; Δt, sampling interval; PV_t, controlled variable; Z_t, controlled deviation ($Z_t = DV - PV_t$; DV, desired value). Parameters of Δt, K_p, T_I, T_D and DV were set in CPU. Equation (1) is a modified PID algorithm of velocity form in which derivative action was based on controlled variable (PV_t) for reducing overshoot.

For cooling, Y_t calculated in Eq. (1) was transmitted to time division positioner (TDP; XX-9, CHINO WORKS, LTD.) at a given control interval (CI). In the control interval, one of the refrigerators was selected and operated by on-off action based on time division PID control action. This process is shown in the flow chart of Fig. 2: The time ($ONTIME$) when a refrigerator was kept to be "ON" within a given control interval (CI) was proportional to manipulated variables (Y_t) as follows,

$$ONTIME = \frac{Y_t}{100\%} CI \tag{2}$$

For example, when $Y_t = 60\%$ and $CI = 60$ sec, a refrigerator selected for cooling was kept to be "ON" for 36 sec and "OFF" for rest 24 sec of the control interval (60 sec). When the refrigerator received "OFF" signal, the solenoid valve of liquid refrigerant line was closed, but the compressor was not shut down and continued to run for about 20 sec of pumpdown time.

For dehumidifying, Y_t was transmitted to two-value controller (ON-OFF; NB 821, CHINO WORKS, LTD.) at a given sampling interval (Δt). One of the refrigerators was selected and operated by two-value on-off control action, as shown in the flow chart of Fig. 3.

This selective operation of refrigerators for cooling and dehumidifying was employed for following reason: Startup of the refrigerator must be kept waiting for the time when the refrigerant remained in direct-expansion coil and pipe has not been withdrawn to the refrigerator in order to prevent the compressor damage by floodback and flooded start. The time of 90 sec was enough for the withdrawal of refrigerant. This functional restriction makes frequent on-off action impossible and brings difficulty in accurate control of air temperature and humidity. To improve such disadvantage, the four refrigerators shown in Fig. 4 were operated by a sequence

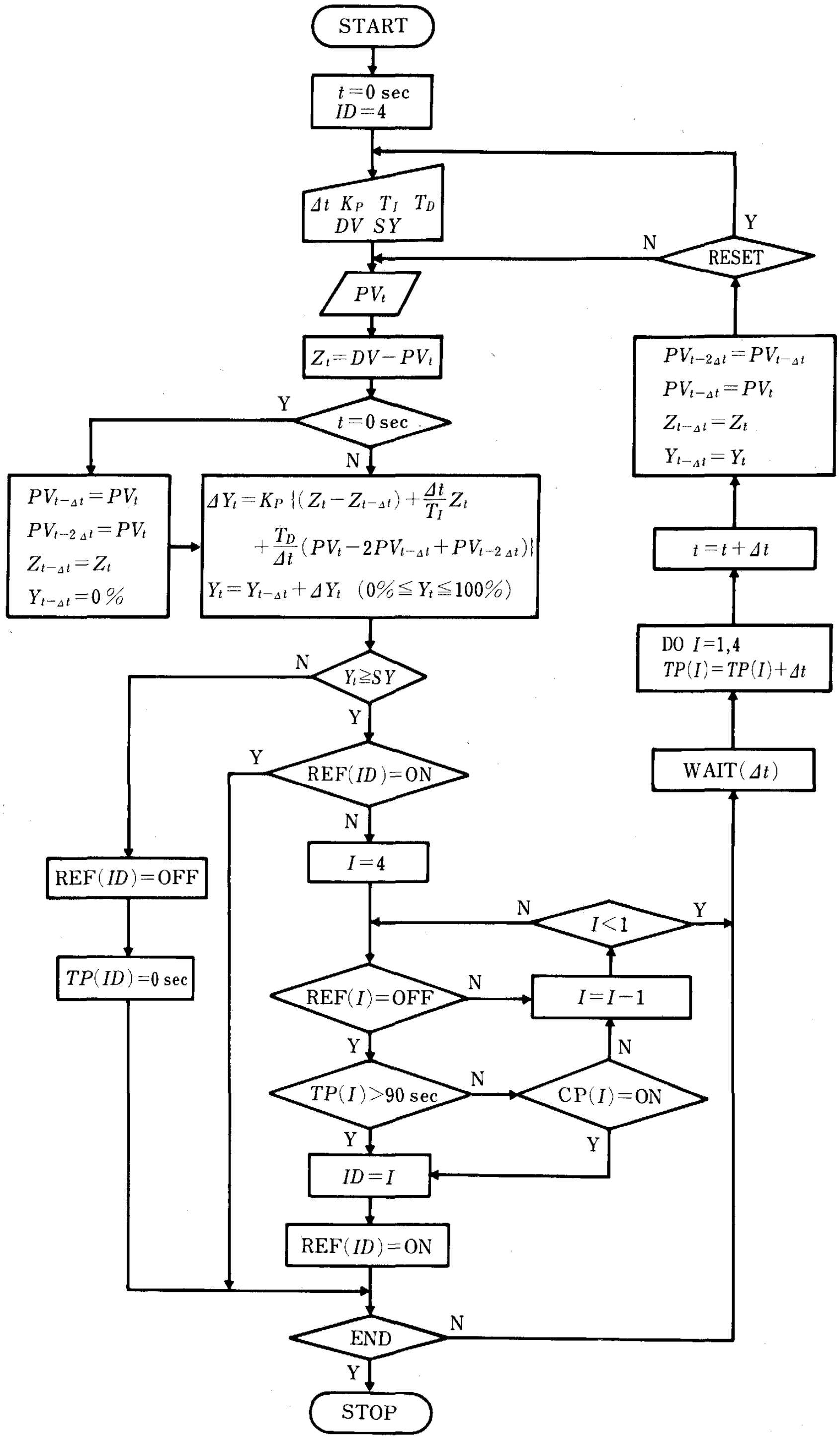

Fig. 3. Flow chart for dehumidifying: t, time; Δt, sampling interval; K_P, proportional gain; T_I, reset time; T_D, rate time; DV, desired value; SY, set value in two-value controller; PV_t, controlled variable; Z_t, controlled deviation; Y_t, manipulated variable; REF, refrigerator; ID, selected REF for dehumidifying; CP, compressor of REF; TP, elapsed time in REF after receiving "OFF" signal.

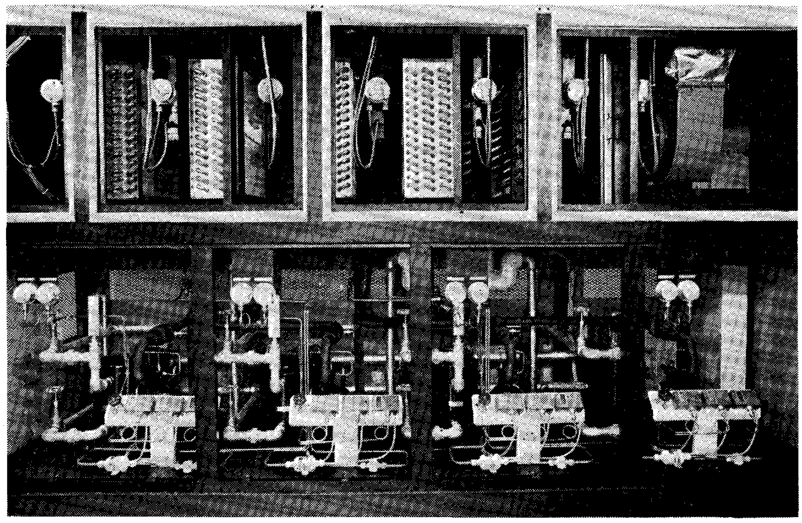

Fig. 4. Photograph of cooling and dehumidifying unit composed of four direct-expansion coils and four refrigerators.

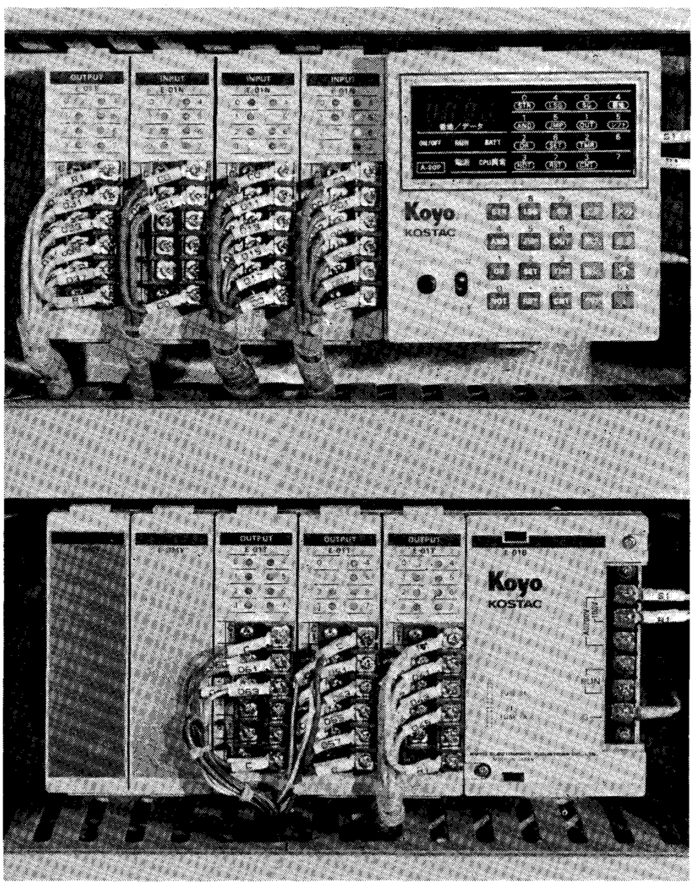

Fig. 5. Photograph of sequence controller for selective operation of refrigerators.

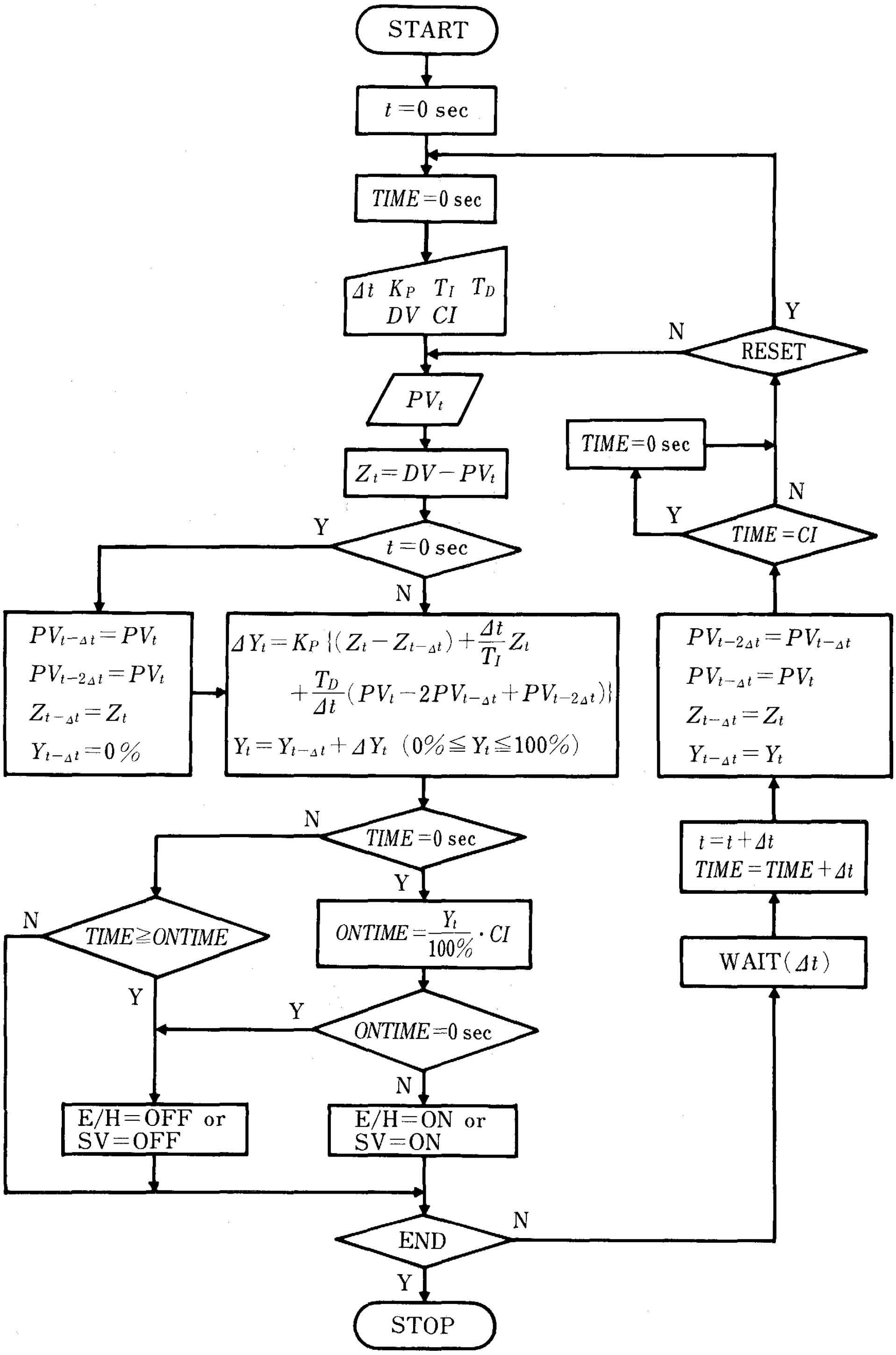

Fig. 6. Flow chart for heating or humidifying: t, time; *TIME*, elapsed time from the start of a control interval; Δt, sampling interval; K_P, proportional gain; T_I, reset time; T_D, rate time; DV, desired value; CI, control interval; PV_t, controlled variable; Z_t, controlled deviation; Y_t, manipulated variable; E/H, electric heating coil; SV, humidifying solenoid valve; *ONTIME*, operating time of E/H or SV in a control interval.

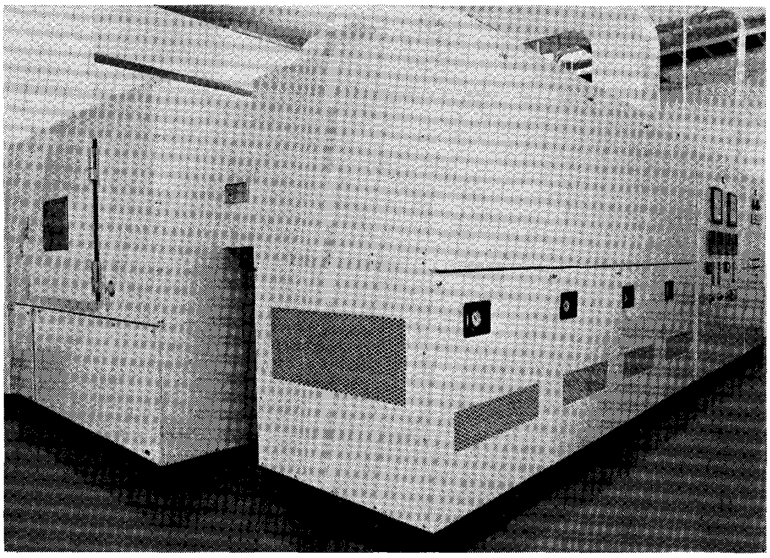

Fig. 7. Photograph of general view of growth chamber.

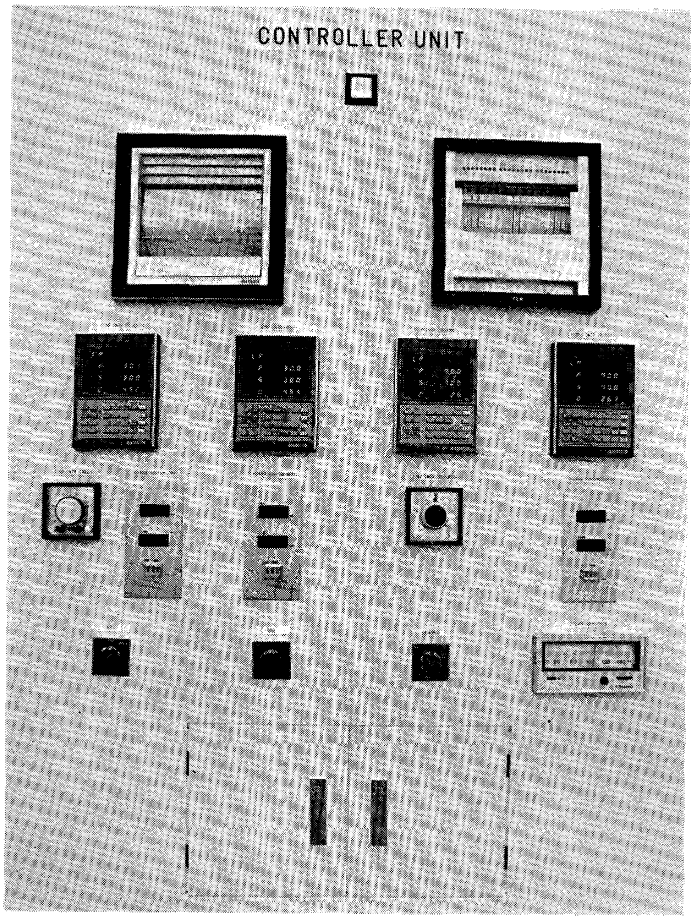

Fig. 8. Photograph of control panel of growth chamber.

controller (SEQ; SA-20, KOYO ELECTRONICS CO., LTD.) which selected one of the refrigerators being on standby. These processes in cooling and humidifying are shown in the flow charts of Figs. 2 and 3: The refrigerator in which the elapsed time (*TP* (*I*)) after receiving "OFF" signal had been longer than 90 sec, was ready for operation. In the case that the pumpdown was not finished and the compressor was running (CP (*I*)=ON), SEQ was able to select again the same refrigerator, even if *TP* (*I*) in a refrigerator was shorter than 90 sec. The priority order in the selective operation was from REF (1) to (4) in cooling and from REF (4) to (1) in dehumidifying. Figure 5 shows a photograph of the sequence controller.

For heating and humidifying, respective manipulated variables (Y_t) were transmitted to time division positioners (TDP) at a given control interval. Electric heating coil was operated by on-off action based on time division PID control action through non-contact relay (SSR). Steam supply from electric boiler was manipulated for humidifying by on-off action of solenoid valve (SV) on the basis of time division PID control action. Flow chart for heating or humidifying is shown in Fig. 6. Figures 7 and 8 show photographs of general view and control panel of the growth chamber, respectively.

CONTROL CHARACTERISTICS

In air temperature and humidity control by the time division PID control action, control interval (*CI*) is one of the important parameters. So, it is necessary to examine control characteristics for optimum setting of the control intervals. In this growth chamber, air was able to be controlled within a range of 40 to 80% RH at 15 to 35°C. In constant-value control of humidity higher than 60%RH, humidity was controlled by only humidifying manipulation as humidifying load was always kept by cooling manipulation. This process without dehumidifying manipulation was reasonable for energy conservation in the higher humidity ranges. In this experiment, static and dynamic characteristics of the control system were examined at different control intervals under two humidity conditions of 70 and 40%RH.

Static characteristics

In constant-value control of air temperature and humidity at respective control intervals (*CI*) of 15, 30, 60, 120 and 240 sec, energy conservation and control accuracy were analyzed. Degree of energy conservation was evaluated by using operation percentages in the final control elements of four refrigerators, electric heating coil and humidifying solenoid valve. Operation percentages in the refrigerators were calculated from operating time of the respective compressors. Control accuracy was evaluated by control area which was measured by integrating absolute controlled deviations with respect to time. In this integration, controlled deviation was treated as 0 in the case that the controlled variable was settled within ±0.3°C and ±3%RH.

Figure 9 shows controlled variables of air temperature and relative humidity at a control interval of 60 sec at desired values of 20 (A) and 30 (B) °C, and of 70%RH. The fluctuations in controlled air temperature and relative humidity were very small and maintained within ±0.3°C and ±3%RH. Table 1 shows operation

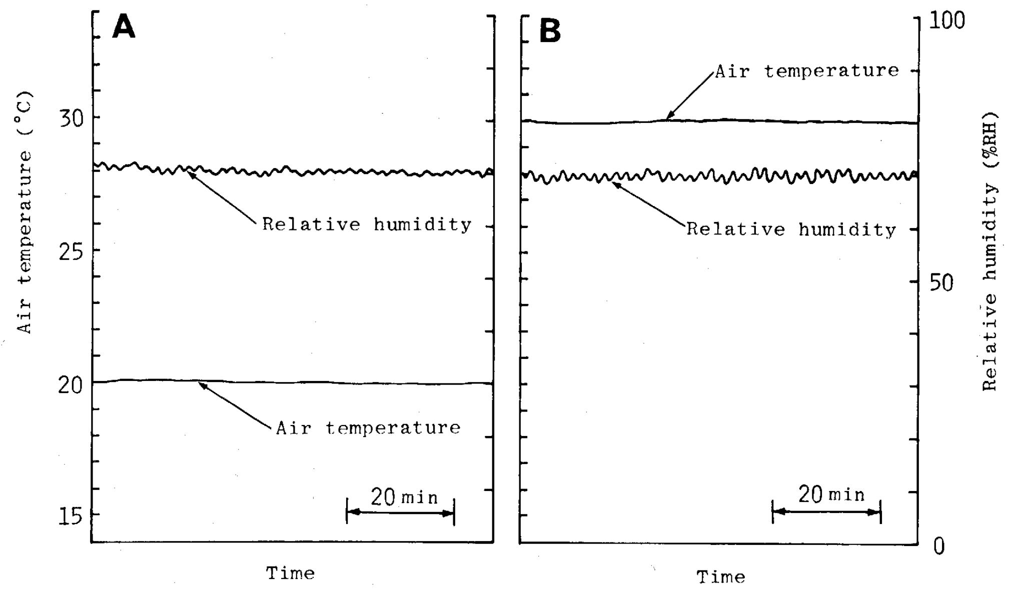

Fig. 9. Controlled variables of air temperature and relative humidity at a control interval of 60 sec at desired values of 20 (A) and 30 (B)°C, and of 70% RH.

Table 1. Operation percentages in final control elements and control areas measured for 1 hr at respective control intervals of 15, 30, 60, 120 and 240 sec at desired values of 20°C and 70% RH.

Control interval in time division PID control action (sec)	Operation percentage (%)							Control area	
	Cooling					Heating	Humidifying	Air temperature (°C min)	Relative humidity (% min)
	Refrigerators				Total	Electric heating coil	Solenoid valve		
	(1)	(2)	(3)	(4)					
15	100	0	0	0	100	26	29	0	0
30	24	25	25	0	74	21	15	0	0
60	26	27	0	0	53	15	9	0	0
120	39	37	0	0	76	22	26	0	14
240	37	41	0	0	78	24	24	0	32

percentages and control areas measured for 1 hr at respective control intervals of 15, 30, 60, 120 and 240 sec at 20°C and 70%RH. In distribution of operation percentage in the refrigerators, it was found that the refrigerators were selected for operation of cooling in the priority order from REF (1) to (4) by the sequence controller in control intervals of 30 to 240 sec. At control interval of 15 sec, however, REF (1) received repeatedly "ON" signal before the pumpdown had finished and the compressor had shut down, and it was kept to be running (CP (1)=ON) as shown in Fig. 2. Operation percentages became lowest at a control interval of 60 sec. At control intervals of 15, 30, 60 sec, respective controlled deviations of air temperature and relative humidity were always maintained within ±0.3°C and ±3%RH, and control areas were evaluated as 0. On the other hand, control areas of relative humidity became larger at control intervals of 120 and 240 sec. Table 2 shows operation percentages and control areas at 30°C and 70%RH. Operation percentages were remarkably lower at control intervals of 60 and 240 sec. However, control areas in relative humidity became remarkably large at control interval of 240 sec.

Figure 10 shows controlled variables of air temperature and relative humidity at a control interval of 60 sec at desired values of 20 (A) and 30 (B) °C, and of 40%RH. Controlled air temperature and relative humidity fluctuated to some extent, but respective controlled deviations were maintained mostly within ±0.3°C and ±3%RH. Table 3 shows operation percentages and control areas at respective control intervals of 15, 30, 60, 120 and 240 sec at 20°C and 40%RH. Distribu-

Table 2. Operation percentages in final control elements and control areas measured for 1 hr at respective control intervals of 15, 30, 60, 120 and 240 sec at desired values of 30°C and 70% RH.

Control interval in time division PID control action (sec)	Operation percentage (%)							Control area	
	Cooling					Heating	Humidifying	Air temper-ature (°C min)	Relative humidity (% min)
	Refrigerators				Total	Electric heating coil	Solenoid valve		
	(1)	(2)	(3)	(4)					
15	15	22	19	12	68	23	21	0	0
30	22	23	23	0	68	24	22	0	0
60	21	20	0	0	41	19	6	0	0
120	27	21	0	0	48	25	18	3	19
240	27	0	0	0	27	11	11	0	477

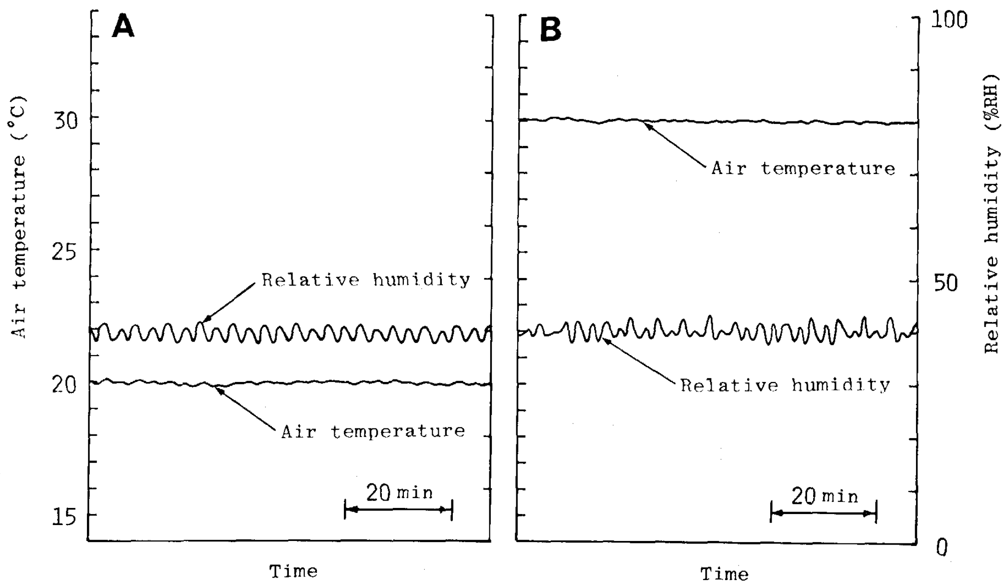

Fig. 10. Controlled variables of air temperature and relative humidity at a control interval of 60 sec at desired values of 20 (A) and 30 (B) °C, and of 40% RH.

Table 3. Operation percentages in final control elements and control areas measured for 1 hr at respective control intervals of 15, 30, 60, 120 and 240 sec at desired values of 20°C and 40%RH.

Control interval in time division PID control action (sec)		Operation percentage (%)								Control area	
		Cooling and dehumidifying						Heating	Humidifying	Air temperature (°C min)	Relative humidity (% min)
		Refrigerators				Total		Electric heating coil	Solenoid valve		
		(1)	(2)	(3)	(4)						
15	Cooling	45	29	14	0	88	139	63	10	2	30
	Dehumidifying	0	6	24	21	51					
30	Cooling	31	38	16	0	85	138	64	9	0	0
	Dehumidifying	0	2	27	24	53					
60	Cooling	39	41	0	0	80	141	67	7	0	0
	Dehumidifying	0	0	34	27	61					
120	Cooling	27	27	0	0	54	129	62	8	0	15
	Dehumidifying	0	0	44	31	75					
240	Cooling	48	0	0	0	48	123	59	9	1	55
	Dehumidifying	0	0	40	35	75					

Table 4. Operation percentages in final control elements and control areas measured for 1 hr at respective control intervals of 15, 30, 60, 120 and 240 sec at desired values of 30°C and 40% RH.

Control interval in time division PID control action (sec)		Operation percentage (%)								Control area	
		Cooling and dehumidifying						Heating	Humidifying		
		Refrigerators				Total		Electric heating coil	Solenoid valve	Air temperature (°C min)	Relative humidity (% min)
		(1)	(2)	(3)	(4)						
15	Cooling	64	23	1	0	88	144	72	11	0	17
	Dehumidifying	0	0	31	25	56					
30	Cooling	20	15	15	0	50	103	66	9	0	36
	Dehumidifying	0	15	19	19	53					
60	Cooling	26	27	0	0	53	113	68	8	0	2
	Dehumidifying	0	0	34	26	60					
120	Cooling	44	0	0	0	44	106	68	8	0	2
	Dehumidifying	0	0	38	24	62					
240	Cooling	42	0	0	0	42	103	64	8	3	4
	Dehumidifying	0	0	34	27	61					

tions of operation percentage in the refrigerators for cooling and dehumidifying indicated that the refrigerators were selected for operation in the respective priority orders. Any appreciable difference among the control intervals was not found in operation percentage. However, control areas in air temperature and relative humidity were smallest (0) at control intervals of 30 and 60 sec. Table 4 shows operation percentages and control areas at 30°C and 40%RH. There were no significant differences in operation percentage among the control intervals. Control areas in air temperature were 0 at the all control intervals except for 240 sec. In relative humidity, control areas were remarkably small at control intervals of 60 and 120 sec.

From the results obtained in static characteristics, it could be conceivable that this system can be optimalized for accurate control and energy conservation by setting the control interval at 60 sec.

Dynamic characteristics

In step responses of air temperature from 20 to 30°C and from 30 to 20°C, dynamic characteristics of the control system were examined by measuring settling time and control area. In this experiment, settling time was defined as the time when controlled air temperature was settled within ±0.3°C around the desired value. Control area was measured in the same manner described above.

Figure 11 shows the step responses of air temperature from 20 to 30°C (A) and from 30 to 20°C (B) at a control interval of 60 sec at 70%RH. In these step responses, overshoot of about 2°C was found, but controlled air temperatures were settled within about 50 min (settling time). Controlled relative humidity fluctuated to some extent, but the controlled deviation was mostly maintained within ±3%RH. Figure 12 shows the distributions of settling times and control areas on the control

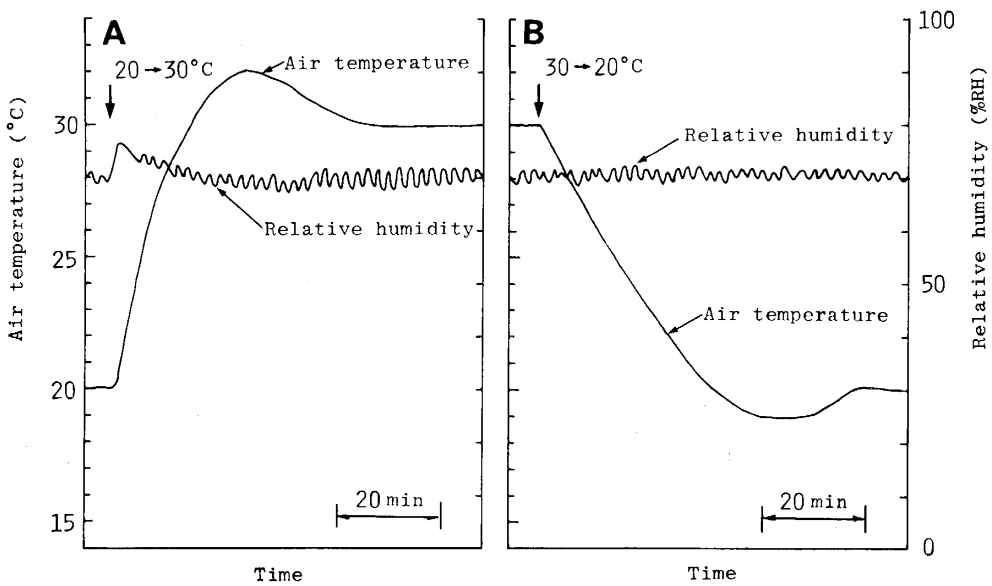

Fig. 11. Step responses of air temperature from 20 to 30°C (A) and from 30 to 20°C (B) at a control interval of 60 sec at 70% RH.

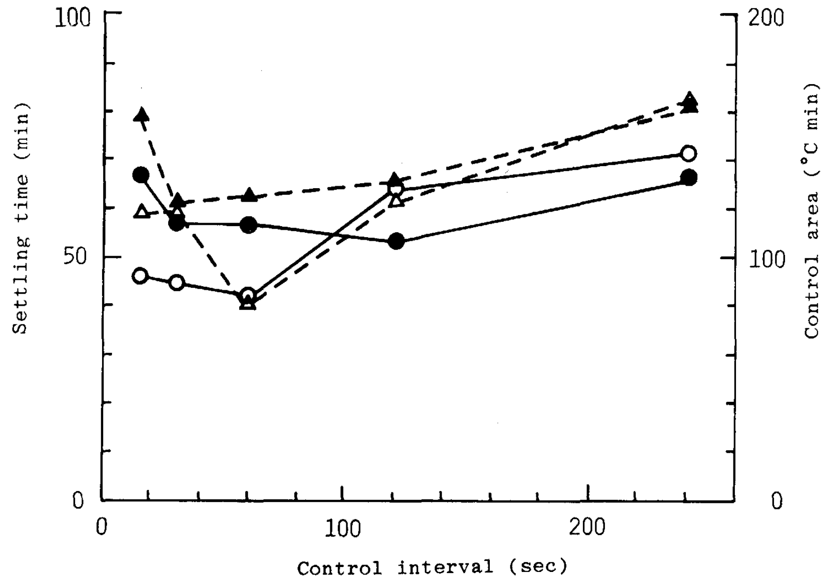

Fig. 12. Distributions of settling times (○ and ●) control areas (△ and ▲) on control interval in step responses of air temperature from 20 to 30°C (open symbols) and from 30 to 20°C (closed symbols) at 70% RH.

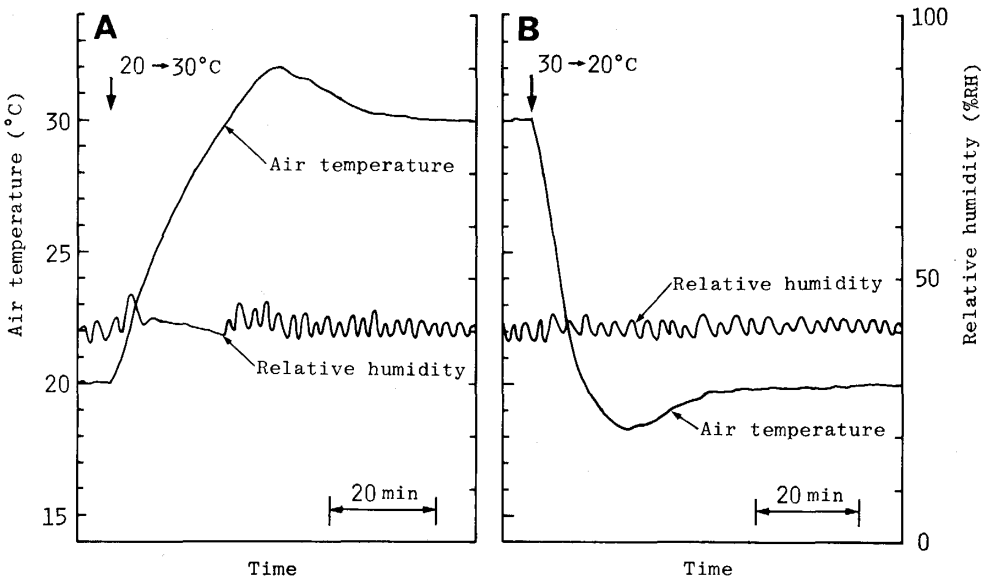

Fig. 13. Step responses of air temperature from 20 to 30°C (A) and from 30 to 20°C (B) at a control interval of 60 sec at 40% RH.

interval in the step responses of air temperature at 70%RH. Both of settling time and control area were found to be minimized at control intervals of 30 and 60 sec.

Figure 13 shows the step responses of air temperature at a control interval of 60 sec at 40%RH. In these step responses, controlled air temperatures were settled within about 50 min in rising and 30 min in falling. Fluctuation of controlled relative humidity were maintained approximately within ± 3%RH. Figure 14 shows

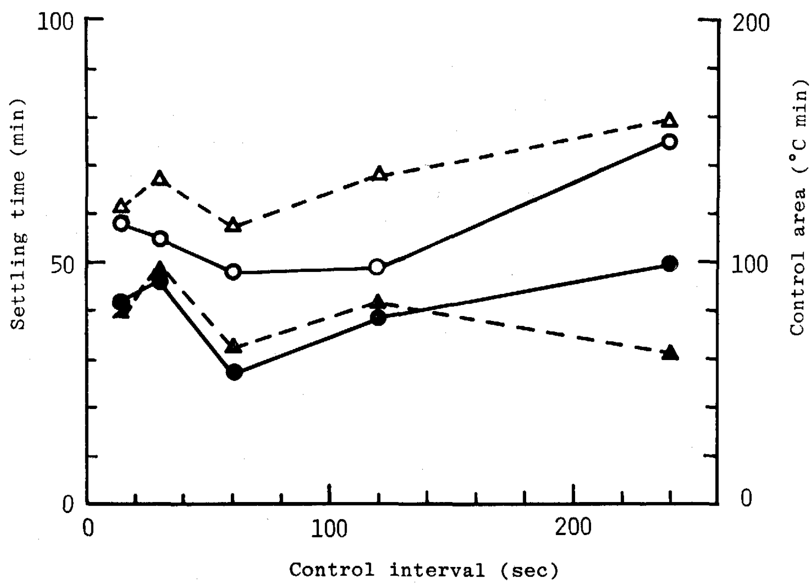

Fig. 14. Distributions of settling times (○ and ●) and control areas (△ and ▲) on control interval in step responses of air temperature from 20 to 30°C (open symbols) and from 30 to 20°C (closed symbols) at 40% RH.

the distributions of settling times and control areas on the control interval in the step responses of air temperature at 40%RH. The settling time and the control area were influenced by the control intervals and it was found that both of settling time and control area became minimum at control interval of 60 sec.

From these results, it was estimated that control interval of 60 sec is optimal for dynamic characteristics.

CONCLUSION

The time division PID control action was applied to accurate and energy conservative control of air temperature and humidity in a growth chamber with four direct-expansion coils. Control characteristics were analyzed in relation to optimum setting of the control intervals of the time division PID control action, and the interval of 60 sec was found to be optimal for accurate control and energy conservation: This system made it possible to control air temperature and humidity within ±0.3°C and ±3%RH around the respective desired values even under the energy conservative condition. Furthermore, this system might be optimalized in more details by improving the control algorithm and adjusting other parameters (*5*).

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