

INFLUENCE OF FAULT AND OPTIMIZATION OF PID PARAMETERS IN BUILDING AIR-CONDITIONING SYSTEM

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ABSTRACT

This paper addresses the effects of fault and optimization of PID parameters in building air-conditioning systems. On setting disorder of PID parameters, the influence was made clear through an experiment and numerical simulation. It produced hunting at VVW 2-way valve, etc. larger than the difference of electricity consumption and the room's temperature fluctuation. And it caused vibration at the supply air temperature and the chilled water temperature, etc. It also affected the increase of the ON/OFF frequency of the chiller. On the optimization of PID parameters, optimum adjusting strategy using GA was proposed. The strategy simultaneously searches two kinds of PID parameters of VVW 2-way valve and VAV unit. As a result of the calculation, it was confirmed that GA was an effective strategy when PID parameters of the multiple controls were found.

INTRODUCTION

Improper operations and invisible faults in the air-conditioning systems caused increases of energy consumption and deterioration of the indoor environment. In order to stock high-quality buildings, the energy demands of the owner need to be known to realize and maintain the building equipment performance throughout the life cycle.

Because the structure is comparatively simple and it is possible to adjust parameters on the spot, PID control is widely adopted as one of feedback controls. But adjusting of parameters needs engineers' experience and it is sometimes set through trial-and-error with much time and labor. Because the building air-conditioning is left to the owner's discretion after the building is completed and the warranty term is finished, the building's air-conditioning system is often operated under improper conditions with setting disorder PID parameters and go unnoticed. In such buildings, not only cannot the room's temperature be adequately controlled, but also the system components may be damaged by deterioration from oscillation of the components themselves (valve, dumper, etc.).

There have been studies done on adjusting strategy of PID parameters by Niwa and Sagara et al. in the field of building air-conditioning systems in Japan [1, 2]. Niwa et al. have verified the applicability of limit sensitivity method and step response method as classical control parameter tuning methods in air-conditioning systems. And Sagara et al. have estimated optimum PID values referring to an evaluation function considering largest deviation and the speed for responses, etc. Though these studies have been conducted in a specific control, multiple PID controls are adopted in actual air-conditioning systems. And each control is a complicated interaction. Even if PID parameters are assumed to be appropriate in a specific control, there is no guarantee that the parameters will be optimum for the cases in which the whole system is operated. Then it is desirable to simultaneously adjust PID parameters of the multiple controls.

From the viewpoint of the appropriate operation of buildings, we examine the influence of fault and optimization of PID parameters in the air-conditioning systems. On the fault of PID parameters, the influence is verified through experiment and numerical simulation. On the optimization of PID parameters, the possibility of simultaneous adjusting strategy of PID parameters of the multiple controls is examined using a genetic algorithm (GA). It simulates mechanisms of organisms' heredity and evolution.

We called the object for experiment and numerical simulation "HVAC&R Experimental Analysis System". This facility has the air-conditioning systems (center supply system using an air-handling unit (AHU)) widely introduced in buildings. By freely changing the control system and control parameters in proportion to experiment menus, it is possible to intentionally cause improper operations and faults in the facility. The HVAC&R Experimental Analysis System is described in the next chapter.

OUTLINES OF HVAC&R EXPERIMENTAL ANALYSIS SYSTEM

The HVAC&R Experimental Analysis System is composed of an air source heat pump chiller, a primary pump, an air handling unit (AHU) and a

secondary pump. The following are shown in Figure 1, Figure 2, Figure 3, Picture 1, Table 1: first floor plan, sectional plan, air-conditioning system figure, outside of the HVAC&R Experimental Analysis System and specifications of equipments. And performance characteristics of the chiller are shown in Figure 4. ON/OFF control is carried out at the chiller. In cooling mode, the chiller begins operation if the primary outlet chilled water temperature rises over 5K more than the preset temperature. It stops operation if the temperature falls 3K less than the preset temperature. In heating mode, it begins operation if the primary outlet chilled water temperature falls 5K less than the preset temperature. It

stops operation if the temperature rises over 3K more than the preset temperature. The preset value of the primary outlet chilled water temperature is 7deg.C in cooling mode and 45deg.C in heating mode. VVW 2-way valve is controlled so that the air supply temperature becomes the preset temperature by PI control. Bypass valve can be adjusted so that the piping internal pressure inlet the AHU becomes the preset pressure by PI control. VAV unit controls the damper so that the room's temperature becomes the preset temperature by PI control, and adjusts the air flow volume. At the humidistat, ON/OFF control is carried out by reading the first floor's indoor humidity. In the present system, there are restrictions on the experiment. So it will be improved in order to be able to correspond to wider

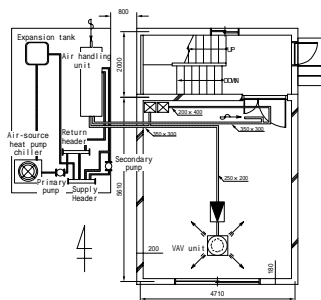


Figure 1. First Floor Plan

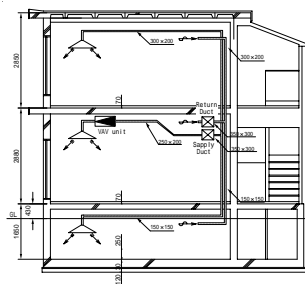


Figure 2. Sectional Plan



Picture 1. Outside Of HVAC&R Experimental Analysis System

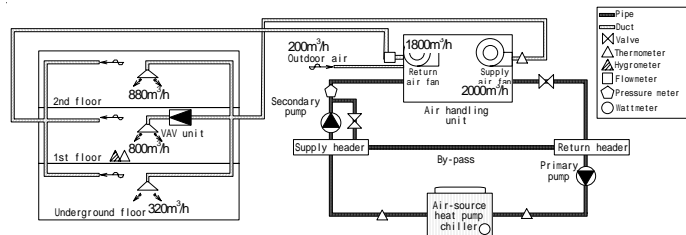
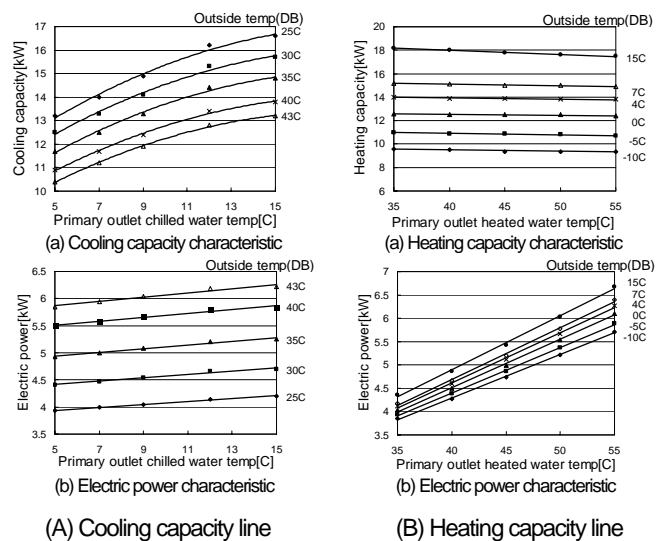


Figure 3. Air-Conditioning System Figure

Table 1. Specifications of Equipments

Equipment	Specification	
Air handling unit	Cooling capacity	10.5 kW
	Heating capacity	10.5 kW
	Chilled water flow rate	1.86 m³/h
	Supply air fan	Rating supply air volume
Return air fan	Rating input value	1.5 kW
	Rating return air volume	1800 m³/h
Humidistat	Rating input value	1.5 kW
	Vaporization system type	
Air source heat pump chiller	Available vaporization volume	2.0 kg/h
	Cooling capacity	12.5 kW
	Heating capacity	15.0 kW
	Rating input value: COOL	5.0 kW
Primary pump	Rating input value: HEAT	5.2 kW
	Line type	
Secondary pump	Chilled water flow rate	2.7 m³/h
	Rating input value	0.4 kW
	Line type	
Supply header	Chilled water flow rate	2.4 m³/h
	Rating input value	0.4 kW
Return header	Size	65xL800
	Size	65xL800



(A) Cooling capacity line (B) Heating capacity line

Figure 4. Performance Characteristic Lines Of Air Source Heat Pump Chiller

experiment menus by additional introduction of other VAV units, inverters and lots of sensors, etc. in future.

FAULTS OF PID PARAMETERS

Verification By Experiment

Outlines of experiment.

An experiment studying the influence of setting disorders of PID parameters (Proportional gain and Integral time) on the air-conditioning system performance was done. We compared the input of inappropriate values to PID parameters of VWV 2-way valve (fault case) with the input of proper values (appropriate case). VWV 2-way valve is controlled so that the supply air temperature becomes the preset temperature by PI control. The experiment was carried out from 0:30-1:30 (appropriate case) and 1:50-2:50 (fault case) on 21st March, 2005. The outside temperature was around 4deg.C in the experiment period, and it is possible to consider the heating load as almost equal. The experiment was carried out by setting the room's temperature to 20deg.C, air supply temperature to 35deg.C, the primary chilled water temperature to 45deg.C and the piping internal pressure inlet the AHU to 160kPa. PID parameters for the experiment is shown on Table 2.

Experiment results.

Results of the experiment are shown on Figure 5. Although VWV 2-way valve generated hunting and the supply air temperature vibrated, VAV damper was fixed at full gate opening. And the room's temperature was controlled around the preset temperature (20deg.C) in the both cases of appropriate and fault. The following are mentioned as reasons: The heating load in the experiment was large and the response to the room's temperature is gentle since a heat capacity of the building is large. Electricity consumption of the chiller in the experiment period was 3,391Wh in the appropriate case and 3,061Wh in the fault case. The electricity consumption of the fault case was less than the appropriate case. If such a case happens in actual buildings, it is considered that the setting disorder is not noticed, even if only the room's temperature and electricity consumption of the chiller are watched. If results are observed more in detail, we see that the bypass valve

Table 2. PID Parameters Of VWV 2-way Valve For Experiment

	Kc [-]	Ti [s]
APPROPRIATE	1	30
FAULT	20	30

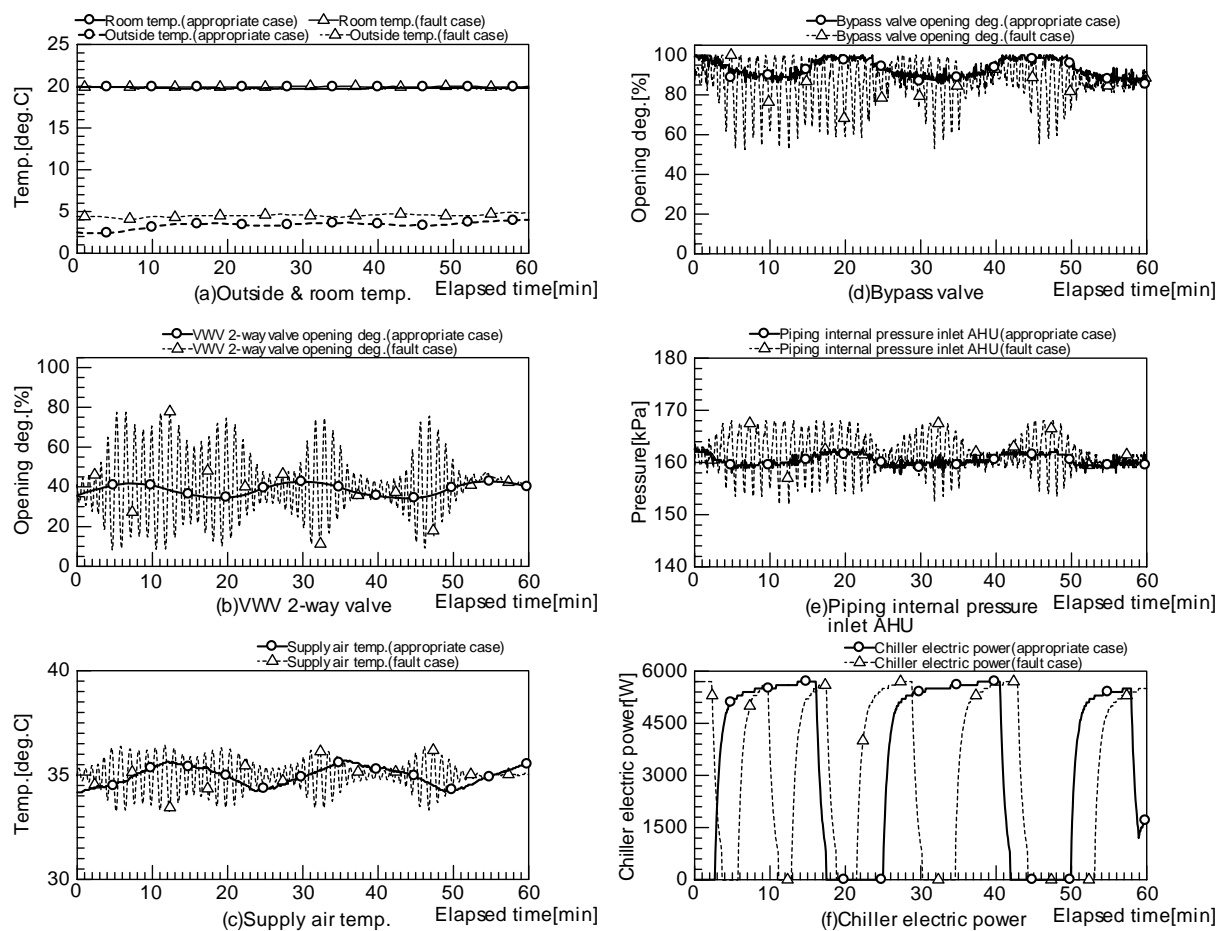


Figure 5. Experiment Results

vibrates. So the piping internal pressure inlet the AHU cannot be properly controlled. And it has also been proven that ON/OFF frequency of the chiller in the fault case doubles when we look at the transition of the electric consumption of the chiller. These may have a large effect on the degradation of the chiller and other element equipments.

Verification By Numerical Simulation

Method and condition of calculation.

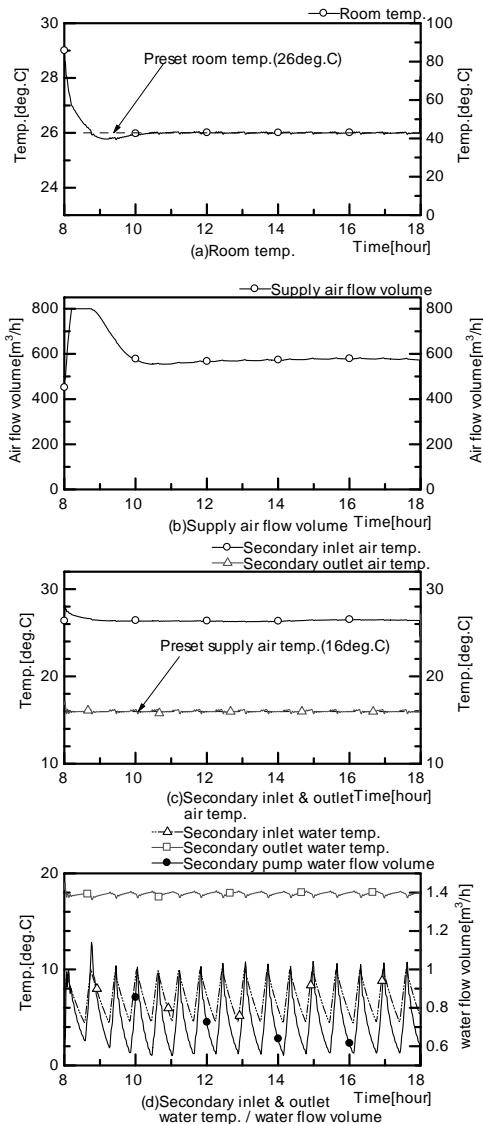
In the thermal load calculation in the building, we used HASP/ACLD/8501 [3] that was improved to be able to calculate in 1 minute increments. In the air-conditioning systems, modules were made referring to the calculation of existing air-conditioning system simulation programs of HASP/ACSS/8502 [4] and HVACSIM+(J) [5], etc. The simulation program we used was constructed by integrating

the calculation of the building and air-conditioning system. Using the simulation program for the HVAC&R Experimental Analysis System, effects of PID parameters of VVW 2-way valve setting disorder on the air-conditioning system performance were made clear. Calculation time step was done in 1 minute increments.

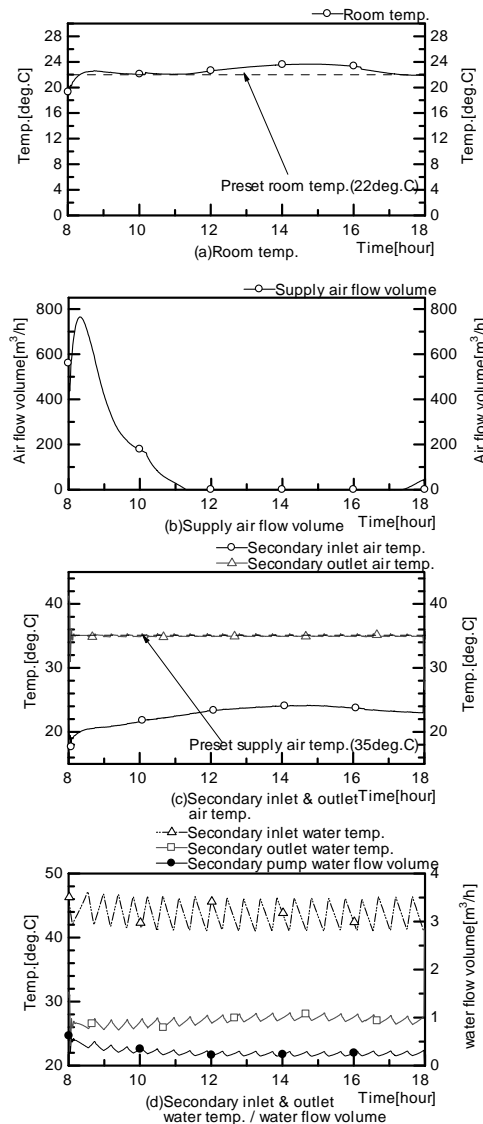
On the control, the following were carried out as well in the system: The supply air temperature was controlled by VVW 2-way valve and the supply air flow volume was controlled by the first floor VAV unit. At the chiller, ON/OFF control was carried out as well in the actual system, too. The control of piping internal pressure by bypass valve

Table 3. Search Range For All Possible Regression

	Kc [-]	Ti [s]	Total
VVW 2WAY VALVE	0.001~0.200 (0.001 step)	0~200 (5sec. step)	8,000 ways



(A) Representative day in Summer.



(B) Representative day in Winter.

Figure 6. Calculation Results (Appropriate Case)

introduced in the actual system is not simulated in this calculation. The room used for calculation was on the first floor. Cooling mode period in summer is from June to September and heating mode in winter is from December to March. It is 8:00-18:00 in the air-conditioning period. The preset room's temperature was 16deg.C in summer and 22deg.C in winter and the preset supply air temperature was 16deg.C in summer and 35deg.C in winter. The pump always runs at the rated flow. The calculations were carried out on typical summer and winter days.

First, the calculation was carried out using the appropriate values as PID parameters of VWV 2-way valve. The PID parameters were searched using the combination in which evaluated value shown in equation 1 became a minimum. The range for search is shown on Table 3. And we examined a case which used optimum PID

parameters in winter (summer) during summer (winter) as the setting disorder. PID parameters of VWV 2-way valve for the calculation is shown at Table 4.

$$VALUE = \sum |F1ATO - F1ATOSP| \text{ (equation 1)}$$

where F1ATO is supply air temp.(deg.C) and F1ATOSP is preset supply air temp.(deg.C)

Calculation results.

The results of the calculation in the case of appropriate and fault are shown in Figure 6, Figure 7. The rise of the room's temperature is seen on winter afternoon. This

Table 4. PID Parameters Of VWV 2-Way Valve For Calculations

	SUMMER		WINTER	
	Kc [-]	Ti [s]	Kc [-]	Ti [s]
APPROPRIATE	0.028	10	0.015	20
FAULT	0.015	20	0.028	10

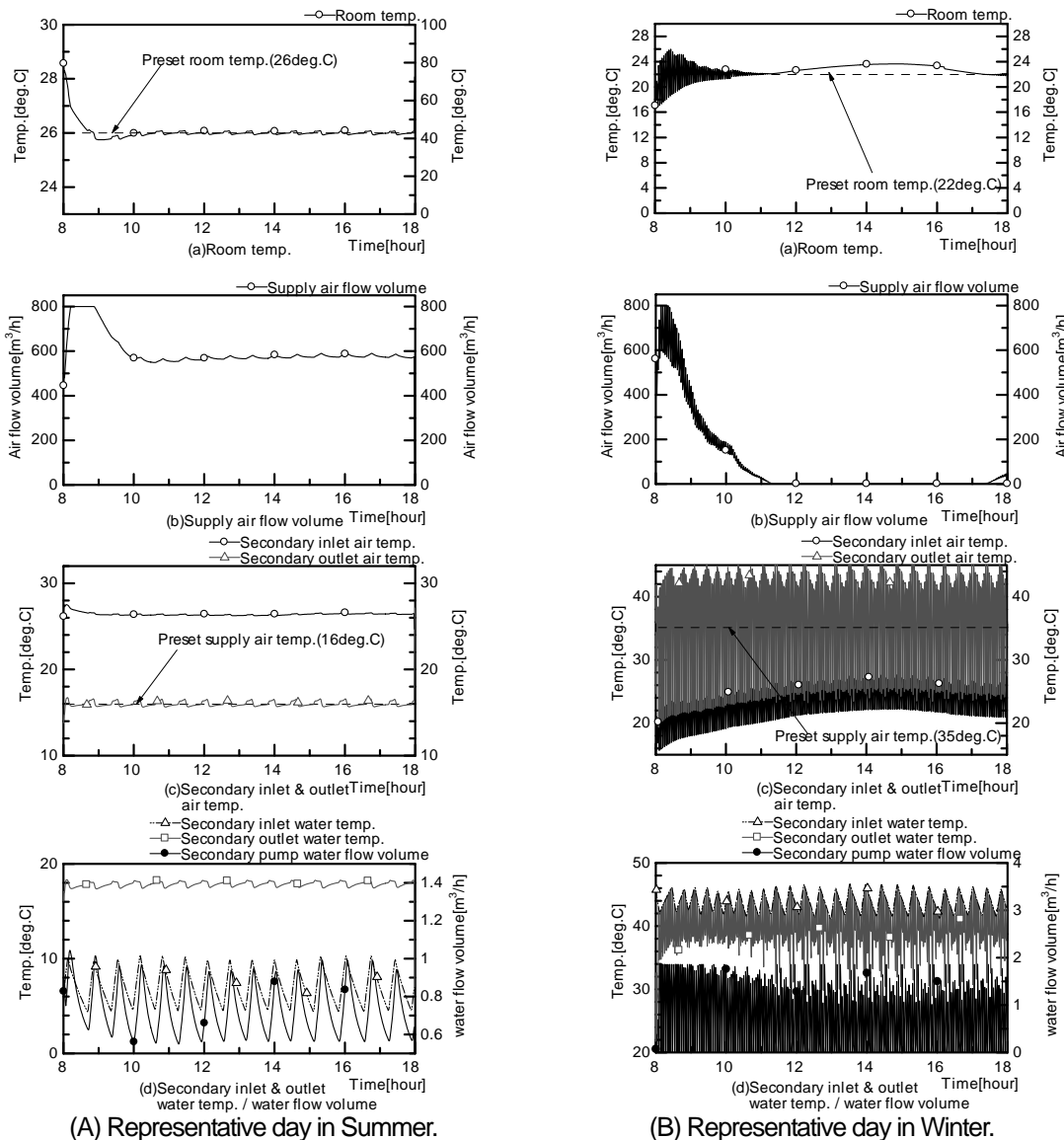


Figure 7. Calculation Results (Fault Case)

corresponds with internal heat generation and effect of the insolation. Since it deals with only heating mode operation in winter and is impossible to deal with. On a summer day, in comparison with a room's temperature fluctuation in the case of appropriate and fault, the temperature can be approximately controlled, though it slightly fluctuates around the preset temperature in the fault case. On the other hand, there was comparatively large vibration of the room's temperature in the fault case on a winter day for about 3 hours after the air-conditioner started. Concerning the secondary inlet and outlet air temperature, the chilled water temperature and flow rate, these repeated large vibration over the vibration of the room's temperature and humidity throughout the whole air conditioning period. Yearly electricity consumption included fan, pump and the chiller was 10,522kWh in the appropriate case and 10,629kWh in the fault case. There were not such a big difference. This is dangerous because operation may continue without the setting disorder of PID parameters being noticed. Even if electricity consumption and the room's temperature and humidity have been noticed.

OPTIMIZATION OF PID PARAMETERS

Optimum Adjusting Strategy Using Genetic Algorithm (GA)

In the preceding chapter, all possible regression was used in order to search appropriate PID parameters of VWV 2-way valve. It was searched in 8,000 ways, so it needed much calculation time. PID parameters of only VWV 2-way valve was searched in the preceding chapter. But actually PID control is also carried out at VAV unit. And the parameters input to the VAV unit also influence air-conditioning system performance. So it is desirable that PID parameters in both VAV unit and VWV 2-way valve are simultaneously adjusted. And it will be searched from the $8,000^2$ (=64,000,000) ways if this is searched using all possible regression, and an enormous calculation time is needed. There are not many points within PID control this time because the building for calculation had a simple air-conditioning system. But much more PID controls are carried out in general office buildings. So it is impossible to simultaneously search each PID parameter using all possible regression. Then, the parameter adjusting strategy using

Table 5. Search Range For GA

	Kc [-]	Ti [s]	Total
VAV UNIT	0.001~1.000 (0.001 step)	0~500 (5sec. step)	100,000 ways
VWV 2WAY VALVE	0.001~1.000 (0.001 step)	0~500 (5sec. step)	100,000 ways

1st generation

No.	2WAY VALVE		VAV UNIT		VALUE
	Kc	Ti	Kc	Ti	
1	0.003	480	0.575	5	143,318
2	0.867	230	0.432	170	181,426
3	0.915	455	0.562	145	181,426
4	0.108	215	0.358	5	180,667
5	0.086	180	0.682	345	164,757
6	0.327	480	0.036	115	177,689
7	0.298	15	0.248	340	178,771
8	0.983	460	0.776	240	181,426
9	0.791	210	0.011	440	177,938
10	0.900	105	0.421	35	181,401
11	0.624	380	0.342	495	181,426
12	0.518	345	0.245	370	181,368
13	0.846	330	0.632	195	181,426
14	0.554	350	0.372	260	181,426
15	0.611	70	0.247	0	181,380
16	0.441	70	0.110	95	178,922
17	0.798	415	0.615	255	181,426
18	0.980	405	0.038	145	177,424
19	0.694	480	0.051	300	177,941
20	0.419	140	0.622	165	181,426

8 combinations in which evaluated value becomes a minimum is left, 6 combinations of which evaluated value is small for the second is left, 4 combinations of which evaluated value is small for the third is left and 2 combinations of which evaluated value is small for the fourth is left.

2WAY VALVE		VAV UNIT	
Kc	Ti	Kc	Ti
0.003	480	0.575	5
0.003	480	0.575	5
0.003	480	0.575	5
0.003	480	0.575	5
0.003	480	0.575	5
0.003	480	0.575	5
0.003	480	0.575	5
0.003	480	0.575	5
0.086	180	0.682	345
0.086	180	0.682	345
0.086	180	0.682	345
0.086	180	0.682	345
0.327	480	0.036	115
0.327	480	0.036	115
0.327	480	0.036	115
0.990	405	0.038	145
0.990	405	0.038	145

PID parameters of VAV unit is changed in the random position.

SELECT →

CROSS ↙

MUTATE →

SELECT →

2WAY VALVE		VAV UNIT	
Kc	Ti	Kc	Ti
0.003	480	0.575	5
0.003	480	0.036	115
0.003	480	0.682	345
0.003	480	0.575	5
0.003	480	0.575	5
0.003	480	0.682	345
0.003	480	0.036	145
0.003	480	0.575	5
0.086	180	0.682	345
0.086	180	0.575	5
0.086	180	0.038	145
0.086	180	0.575	5
0.086	180	0.682	345
0.086	180	0.036	115
0.327	480	0.575	5
0.327	480	0.036	115
0.327	480	0.036	115
0.327	480	0.682	345
0.990	405	0.682	345
0.990	405	0.575	5

The individuals mutates at preset probability (90% at this time). The mutating individual mutates at only a random position among 4 parameters.

2nd generation

No.	2WAY VALVE		VAV UNIT	
	Kc	Ti	Kc	Ti
1	0.003	245	0.575	5
2	0.327	480	0.036	115
3	0.003	480	0.682	345
4	0.003	480	0.583	5
5	0.003	480	0.434	5
6	0.003	480	0.682	410
7	0.003	245	0.038	145
8	0.003	480	0.575	5
9	0.086	180	0.748	345
10	0.642	180	0.975	5
11	0.086	270	0.038	145
12	0.201	180	0.575	5
13	0.086	400	0.682	345
14	0.086	180	0.036	135
15	0.327	480	0.575	410
16	0.327	380	0.036	115
17	0.842	480	0.036	115
18	0.327	480	0.682	345
19	0.822	405	0.682	345
20	0.990	405	0.575	220

SELECT, CROSS and MUTATE is also similarly carried out at the second generation that was generated through such a process.

Figure 8. Outlines Of Optimum Adjusting Strategy By GA

genetic algorithm (GA) which simulates mechanisms of organisms' heredity and evolution is proposed. GA is one of effective strategies to be used in such a case. Because it has approaches both random search strategy (The strategy which considers the combination of all solutions with the possibility and judges whether the solution selected at random from the inside suits the condition.) and a hill-climbing strategy (The strategy which is made to change to the direction in which the evaluation improves from present condition most. There is a high possibility of falling in the localized solution in this strategy.). And GA prevents falling into the limited solution partly because the combination with the most excellent evaluation value is left. The strategy uses the mutation approach.

20 individuals are randomly made from search range (Table 5) as initial values. This is the first generation. As a result of calculating the evaluated value of equation 2 in this combination, 8 combinations in which evaluated value becomes a minimum is left, 6 combinations of which evaluated value is small for the second is left, 4 combinations of which evaluated value is small for the third is left and 2 combinations of which evaluated value is small for the fourth is left (SELECT). Next, PID parameters of VAV unit are changed in the random position (CROSS). Then, it MUTATES at preset probability (90% at this time). The probability here is the one that mutates somewhere

The outlines of optimum adjusting strategy of PID parameters by GA are shown in Figure 8. To begin with,

Table 6. PID Parameters Found By GA

	SUMMER		WINTER	
	Kc [-]	Ti [s]	Kc [-]	Ti [s]
VAV UNIT	0.026	10	0.041	15
VAV 2WAY VALVE	0.024	10	0.017	35

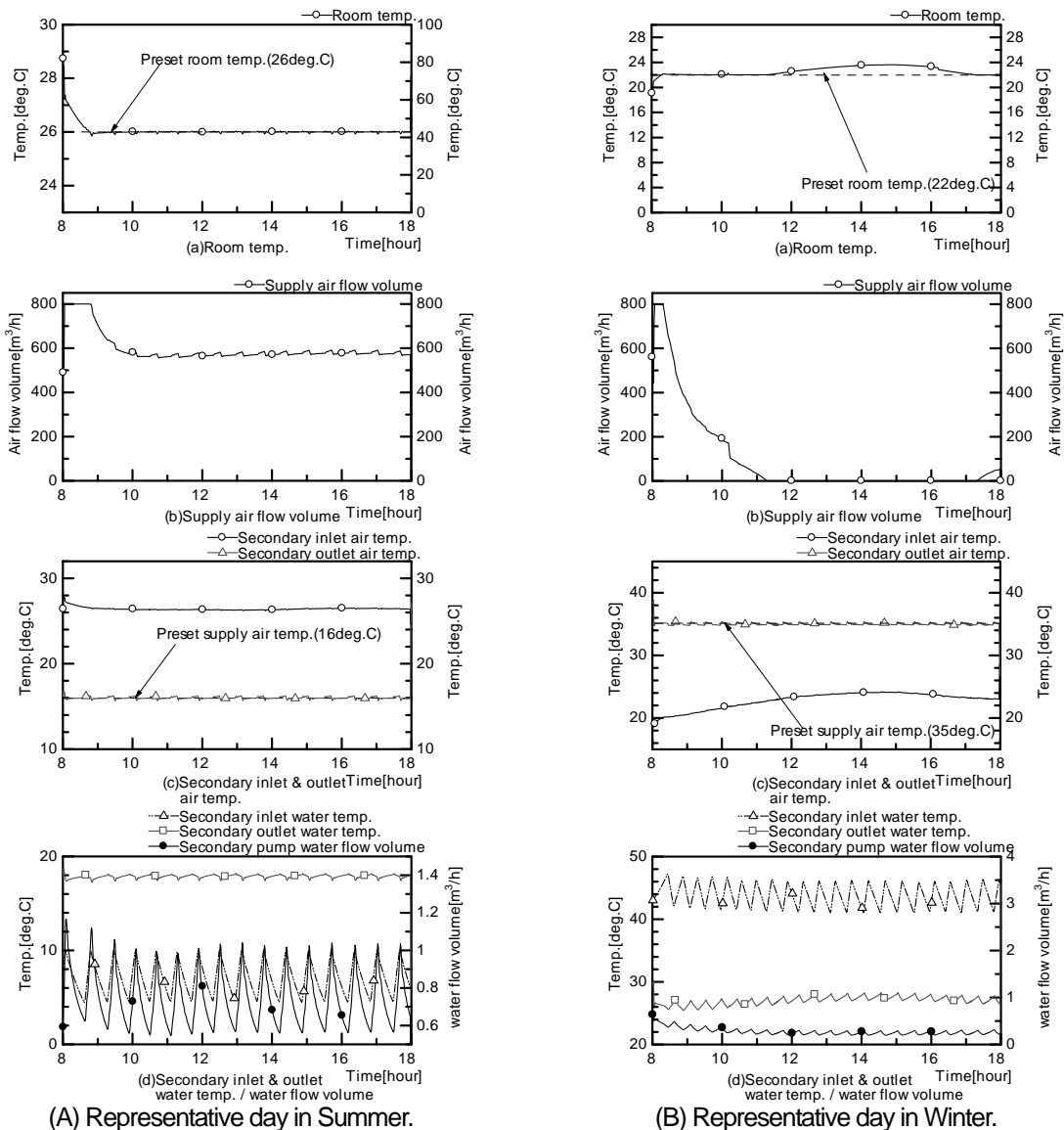


Figure 9. Calculation Results (PID parameters are found by GA)

(Proportional gain and Integral time of VVW 2-way valve and VAV unit). The mutating individual mutates at only a random position among these 4 parameters. SELECT, CROSS and MUTATE is also similarly carried out at the second generation that was generated through such a process. As a result of the calculation to 100 generations, the combination in which evaluated value became a minimum was found.

$$\text{VALUE} = \sum \left((F1ATO - F1ATOSP)^2 + (R1AT - R1ATSP)^2 \right)$$

(equation 2)

where R1AT is room's temp.(deg.C) and R1ATSP is preset room's temp.(deg.C)

Calculation Results

The results of the calculation using optimum PID parameters (Table 6) found by the described strategy are shown in Figure 9. The room's temperature and air supply temperature can be together controlled at the preset temperatures during summer and winter days. So we believe appropriate PID parameters were found. And the room's temperature can be more exactly controlled in comparison with results in the appropriate case in previously stated the "FAULTS OF PID PARAMETERS" section (Figure 6). Because both PID parameters of VVW 2-way valve and VAV unit were simultaneously searched. In spite of simultaneously searching two kinds of PID parameters, the calculation time was shortened to about 1/4 when compared using all possible regression in previously stated the "FAULTS OF PID PARAMETERS" section. These are searched in 2,000 ways: 20 individuals, 100 generations.

CONCLUSIONS

In this study, the effects of fault and optimization of PID parameters in building air-conditioning systems were made clear. On setting disorder of PID parameters, it was found through an experiment and numerical simulation. It produced hunting at VVW 2-way valve, etc. larger than the difference of electricity consumption and the room's temperature fluctuation. And it causes vibration at the supply air temperature and the chilled water temperature, etc. and also affects the increase of the ON/OFF frequency of the chiller. On the optimization of PID parameters, optimum adjusting strategy using GA was proposed. And we simultaneously searched two kinds of PID parameters of VVW 2-way valve and VAV unit. As a result of the calculation, it was confirmed that GA was an effective strategy when PID parameters of the multiple controls were found. Though it was a search for only two kinds of PID parameters this time, we plan to calculate for air-conditioning systems introduced in more general office buildings by using

the same strategy.

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