A COMPARATIVE STUDY OF HVAC DYNAMIC BEHAVIOR BETWEEN ACTUAL MEASUREMENTS AND SIMULATED RESULTS BY HVACSIM+(J)

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ABSTRACT

A dynamic simulation of the HVAC system is being paid attention because of the development of the computer technology. Authors examined the reproducibility of HVACSIM+(J). As current program could not calculate the object system, it was the new component model corresponding to a model system was developed. As the result, it was shown that HVACSIM+(J) have enough reproducibility and possibility to generate the database for the fault detection and diagnosis, FDD, by comparing the simulated results and the measurements. The finding of convenience of HVACSIM+(J) and the points that had to be improved were obtained by experiencing actual simulation work.

INTRODUCTION

In the research and development, or basic plan and design of HVAC system, if the dynamic simulation technique is used, the system can be examined to accord with various users' demands by combining simulation models of various equipments for modeling and remodeling of HVAC system, by setting control parameters and by evaluating system performance. It is difficult to understand exactly and to examine the dynamic behavior by using the conventional static simulation technique, because the HVAC system has a nonlinear characteristic. Dynamic simulation program enabling to analyze systems from such points of view has been thought necessary.

Many research works have been done on dynamic simulations to develop compornents' types, to analyze system behavior and to obtain knowledge database for fault detection, few works can be found concerning to verifying reproducibility of the dynamic characteristics of a HVAC system in total. Authors have already reported a verification result of HVACSIM+(J), modified HVACSIM+, by comparing the actual measurements and simulated values of a simple HVAC system with single duct and constant air volume and achieved a fine precision of reproducibility [1][2].

In the present paper, authors report another result of verification applied to more complicated HVAC system with multi-zone single duct and variable air volume, or VAV, system. First of all, new TYPEs of simulation components and control logic in the object system, which are not included in the current HVACSIM+, were developed. Dynamic data was gathered with actual measurements in the object building. Then reproducibility was evaluated and examined by comparing the measurements and simulated results.

HVACSIM+ AND HVACSIM+(J)

HVACSIM+, Heating Ventilation and Air Condition system SIMulation + other system, that is used for the present research is the dynamic simulation program developed by NIST, National Institute of Standard and Technology, U.S.A. The structural algorithm called as the module method is adopted in HVACSIM+ and simulates the HVAC system, combining the component models, which are called TYPE [3][4][5].

In Japan, after one of the author, Nakahara, obtained the program from NBS, the late name of NIST, in 1987, it has been modified to correspond to Japanese weather data for an authorized air-conditioning load calculation program, called as HASP, and to solve a problem included in flow calculation by developing a new type called as fluid flow network, which calculates the balance of pressure and flow rate of each TYPE and enables back-flow calculation [6]. Moreover, it has been improved to correspond to actual HVAC systems in use in Japan [7] and several TYPEs are modified or newly developed as shown in the this paper. It is now opened to the public as HVACSIM+ Ver.8.1(J) in April 1998 [8][9].

Table 1 Outline of object building and object zone

Object building	Location : Kanagawa Pref. Yokohama-city Completion : 1994 Structure : S+SRC Scale : 1 floor in underground 11 floors on the ground Total floor area : 38,400 m^2 Typical floor area : 1,840 m^2
Object zone	Space Use : Research duty zone Floor area : 819.2 m^2 Ceiling height : 2.7 m

Table 2 Outline of HVAC system

Air-conditioning method	Single duct VAV method (low supply air temperature)
Fan	Supply air flow rate : 12,000 CMH Static pressure : 0.9 kPa
Cooling coil	Face area : 1.417 m^2 EL 1050 mm - 54 steps - 8rows Sensible cooling capacity : 74 kW Total cooling capacity : 97 kW Flow rate : 145 l/min Design temperature : 4-13 C Inside pipe diameter : 8.8 mm Outside pipe diameter : 9.8 mm Fin pitch : 2.3 mm Fin thickness : 0.115 mm
Heating coil	Face area : 1.417 m^2 EL 1050 mm - 54 steps - 4 rows Sensible heating capacity : 43 kW Flow rate : 31 l/min Design temperature : 43-23 C
outside air intake volume	1,725 CMH (constant air volume driven)
VAV unit	Maximum flow rate : 1,500 CMH Minimum flow rate : 360 CMH Electric control Shut off type unit
Two-way valve	Electric ball valve Equal percent characteristic Range ability : 30 : 1 Leakage quantity : less than 0.1% of Cv value Rated pressure : 981 kPa Size : Cooling water 32A Cv value 20 Heating water 20A Cv value 6.6
actuator	Electric control Rotation angle : 90 degrees Operating time : 30 seconds
Energy conservation equipment	Ventilation window with automatic control blind lighting system with daylighting

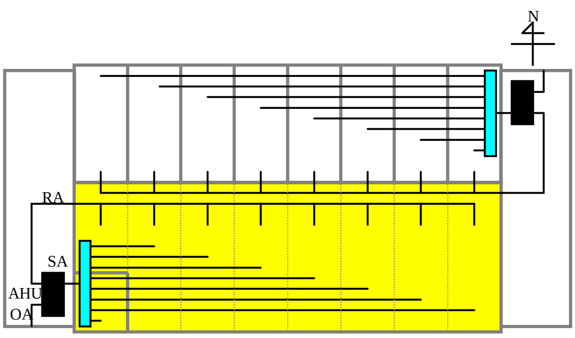

Figure 1 Simplified diagram of typical floor

Table 3 Principal control logic

zone temperature control	PI control by the indoor air temperature, P=2%, I=40min Control range : 24-100% 360-1500CMH VAV opening controlled by the difference between the detection air flow and the demand air flow rate Control cycle : 1 second Continuous mode : Continuously changes, 1.2deg/s, if the difference is 380 CMH or more Step mode : Stop at five seconds after operating one second, if difference is 380 CMH or less Dead band : Hold if the difference becomes 4.5% or less of maximum flow rate
Fan speed control	Controlled by VAV opening signal Reset speed : 1%/1min Increase if there is maximum signal decrease if not is
Cooling water valve control	PID control within the range of 0-80%, P=70%,I=7min,D=0.6min
Supply air temperature reset control	Controlled by maximum/minimum flow rate Reset range : 10-18 degree Maximum flow rate : 80% or more Minimum flow rate : 40% or less Reset speed : 0.5C/20min, after reaching the limit above 0.1C/20min, range between the max. and min.
outside air intake volume control	Controlled by CO_2 concentration of return air with on/off of window ventilation fan If fan drives, 1,725CMH If not, PI control OA volume by damper that CO_2 becomes 900ppm or less, P=3%,I=3min

Table 4 Calculation model flow rate

	(CMH)	(kg/s)
Outdoor air	690-1725	0.23-0.575
Supply air	12000	4
Return air	10275	3.425
Ventilation air	1225	0.4083
Exhaust air	500-1725	0.1667-0.575

OUTLINE OF OBJECT SYSTEM

The object building is situated in Yokohama. Many new technologies for energy conservation and DSM of electricity, such as the ice storage, large temperature difference application in water and air supply, low temperature air distribution, ventilated window, blind and light control, hybrid solar system, etc., were developed and installed.

The HVAC for a typical floor is the single duct VAV, with two air handling units for north private room zone and south open office zone, and with eight VAV units each. The south zone is the objective area of the present paper. The outline of the object building and the object zone is shown in Table 1 and the outline of the HVAC system of the object zone is shown in Table 2. The figure 1 shows simplified diagram of typical floor.

Table 5 Outline of measurement

Date	October 23(Thu)-24(Fri), 1997
Object	South zone in typical floor
Item	Date from Building Management System Number of occupants counted by observation
Interval	1 minute

Table 6 Experiment schedule

State	Date	Situation
Normal	Oct 24(Fri)	Normally controlled
Fault	Oct 23(Thu)	VAV opening of zone 5 was supposed to move between minimum and maximum 12:00 <-> 13:00 : min 13:00 <-> 16:10 : max 16:10 <-> 18:10 : min

OUTLINE OF CONTROL METHOD

The table 3 shows principal control logic of the VAV HVAC system. Every control parameters and set-points were decided following investigation results at the time of measurements.

The air flow rate of the air handling unit for calculation is set as shown in Table 4.

The VAV dampers are controlled by the difference of the demand air flow rate and the detected air flow rate of the attached sensor on the VAV unit as shown in Table 3. The demand air flow rate is decided in the PID controller based on the error between the set point and actual by detected temperature.

The minimum quantity of outdoor air is introduced to satisfy indoor air quality controlled by CO_2 concentration of return air and it should be balanced with the exhaust air flow rate in each floor. The supply air temperature at the outlet of air handling unit is preset at ten degree C, while it is reset by the maximum and minimum air flow rate of each VAV damper as shown in Table 3.

OUTLINE OF MEASUREMENTS

The subject used for evaluating reproducibility is VAV system of south zone at the typical floor. All necessary data for verifying reproducibility of the objective building and HVAC system were measured during a day in every minute. The outline of the measurement is shown in Table 5 and the experiment schedule is shown in Table 6.

As the weather condition of outdoor air temperature, solar radiation, etc. which are necessary for simulation, the measured data on October 23 and 24, 1997 were used, which are shown in Fig.2 and Fig.3. The system was operated normally on Oct. 24 and in a faulty state on Oct. 23. The number of occupants in each zone, which is shown in Table 7 and Table 8, was visually counted every hour during the measurement period and was assumed constant

Table 7 Number of occupants in zone of Oct 24 (person)

Zone	1	2	3	4	5	6	7	8
9 : 10	0	3	1	3	2	3	1	2
10 : 10	0	4	3	5	4	6	5	9
11 : 10	0	4	6	8	1	7	5	9
12 : 30	0	2	2	1	1	4	4	3
13 : 10	0	3	8	6	3	7	4	3
14 : 10	0	3	4	5	2	6	3	5
15 : 10	0	1	4	4	4	3	5	3
16 : 10	0	7	2	6	4	3	4	3
17 : 10	0	4	4	6	3	6	5	3
18 : 20	0	3	4	2	3	2	1	1

Table 8 Number of occupants in zone of Oct 23 (person)

Zone	1	2	3	4	5	6	7	8
9 : 10	0	4	2	2	2	4	1	3
10 : 10	0	10	2	4	5	6	3	3
11 : 10	0	9	5	7	6	6	4	4
12 : 30	0	7	3	5	6	6	1	2
13 : 10	0	7	4	6	5	6	3	2
14 : 10	0	8	4	4	5	1	0	3
15 : 10	0	4	4	6	6	2	4	3
16 : 10	0	7	6	5	5	5	3	3
17 : 10	0	6	5	6	6	5	4	3
18 : 20	0	5	2	1	6	2	2	2

Table 9 Equipment heat generation in each zone

Zone	1	2	3	4	5	6	7	8
kW	0.5	1.5	2.5	3	3.5	2	1.5	1.5

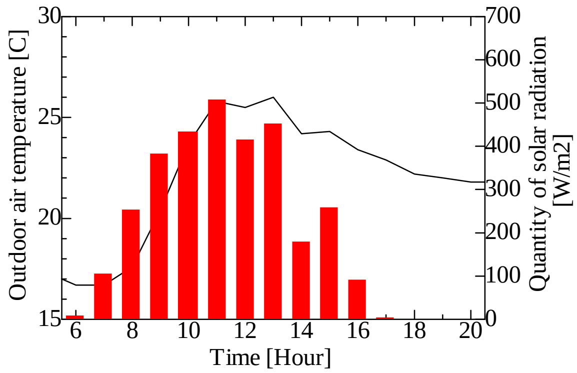

Figure 2 Weather condition at normally state day

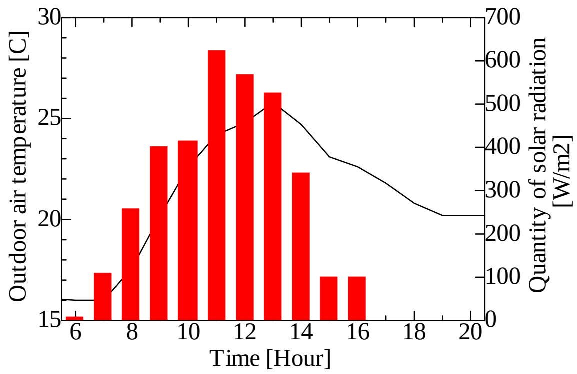

Figure 3 Weather condition at faulty state day

through an hour. Concerning the heat generation rate of the equipment, the specified capacities are used for some specific large scaled equipment such as the copy machines as the actual heat generation rate in relevant spaces. The rated total capacity of heat generation equipments is shown in Table 9. Measured electric power for office automation was allocated in proportion to physical area of zones.

DEVELOPMENT OF NEW COMPONENT MODEL

Due to introduction of new kinds of energy saving techniques installed and new control logic developed for the object building, new TYPEs that were not included in the original program must have been developed. Another type based on an author's past research [10] on energy mixing was also developed in order to raise precision of reproduction.

TYPE406	Mixture loss calculation
TYPE408	Ventilation window
TYPE409	Eaves and louver
TYPE719	Signal resetter by minimum, maximum control signal
TYPE720	Rotation speed controller by the maximum control signal
TYPE730	Signal resetter for VAV
TYPE731	Control signal converter with constant value output for cooling down and warming up
TYPE732	ON/OFF switch by state value
TYPE733	PID Controller (velocity algorithm) with dead band

MODELING OF SIMULATION

After newly developed TYPEs and existing TYPE library were combined, the simulation-modeling file was generated [11].

(1) Assumption at modeling

Efforts were made to model the system as real as possible to simulate actual situation. The following assumptions have been made, however.

a. The zone was divided into eight zones by VAV units and each zone was assumed to be completely mixed. The mixing of the air between adjacent zones was calculated according to a newly developed TYPE406.

b. There is a small partitioned room in zone 1 actually, however, it was assumed that the partition exists between zone1 and zone 2 in calculation, because the control sensor is inside the small partitioned room, while measurements were made outside the partition, so that measured value of air flow rate and temperature did not properly follow the control action. Therefore, the set-point temperature in zone 1 for simulation was replaced with measured values as the boundary data.

Table 10 Operation of VAV

Difference of flow rate	CMH (%)	Below 90 (4.5)	Between 90-380 (4.5-19)	Over 380 (19)
Control range	Deg/s (%/s)	0 (0)	0.2 (0.333)	1.2 (2.0)

c. In calculation, VAV damper is controlled by two steps by the difference of air flow rate in TYPE730 as shown in Table 10. Then, the continuous mode was operated by 1.2 degrees per one second, the step mode was assumed to operate by 1.2 degrees per six seconds, that is 0.2 degrees per one second.

d. The lighting is controlled automatically by brightness in a real building. This will not be simulated and the lighting turn-on rate was input for calculation obtained from lighting power consumption actually measured and was given as the boundary condition.

e. The quantity of the outside air intake is influenced by the drive of the ventilation window fan. However, in the calculation, the set point temperature for on-off of ventilation window fan was adjusted every day so that the quantity of outside air intake meets the actual measurements.

f. The measured value of the inlet water temperature into cooling coil was used as the boundary condition.

g. It was thought impossible to correctly match the simulation condition around the object zone such as elevator hall, etc. with actual condition, so that preliminary calculations were made to decide optimal input values.

(2) Adjustment of parameters

When HVACSIM+(J) was applied for calculation, the data obtained from the design documents and/or as-built records, were used as parameters in the simulation model. However, those parameters which were not obtained from those documents and which seemed to have changed their values by aging were adjusted as follows.

a. No information was obtained from design documents on the effective heat capacity of the furniture and moisture multiplier to adjust the change of the room temperature and humidity, so that they were decided by trial and error as 4286.46[kJ/K] for the heat capacity of the furniture and 1.0 for a moisture multiplier.

b. Errors took place when the measured electric consumption was allocated to each zone in proportion to its physical area, so that the heat generation rate of each zone was somehow adjusted.

c. Heat exchange rate of the cooling coil had lowered compared to the designed value, so that a parameter called as fouling factor was added into the coil TYPE

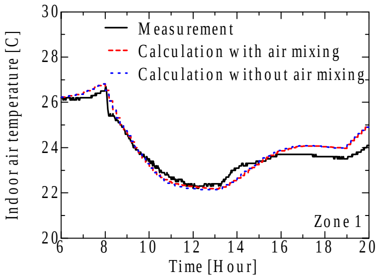

Figure 4-1 Temperature of Zone 1 (Normal State)

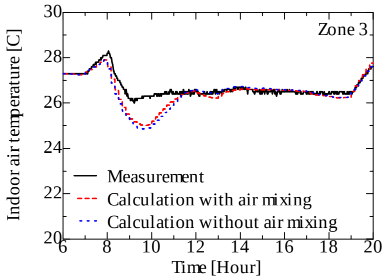

Figure 4-2 Temperature of Zone 3 (Normal State)

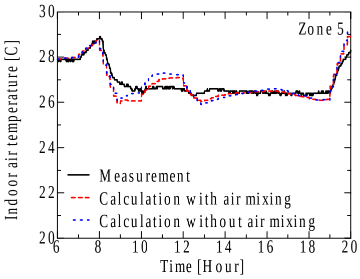

Figure 4-3 Temperature of Zone 5 (Normal State)

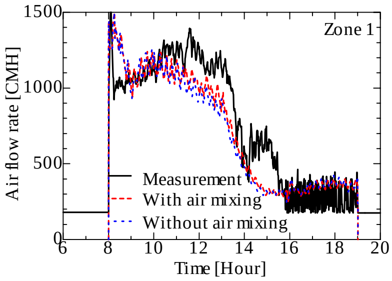

Figure 5-1 Air flow rate of Zone 1 (Normal State)

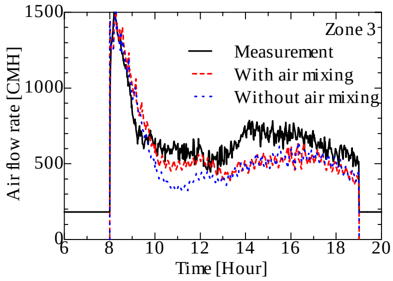

Figure 5-2 Air flow rate of Zone 3 (Normal State)

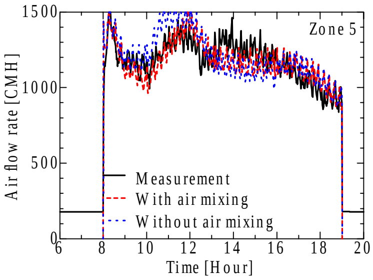

Figure 5-3 Air flow rate of Zone 5 (Normal State)

and adjusted properly to meet the actual measurement value, in consideration to performance decrease of the coil due to contamination on the fin surface.

d. Though the actual air flow is complex and the pass is not definitely identified, the program can represent a predetermined principal air flow pass only. Therefore, the resistance of each circuit must have been properly balanced to adjust the flow rate in the fluid network, which calculates the pressure and flow balance of the air and water network. The entire balancing was performed basically by the rated flow rate, then, in case of the variable flow rate pass, by authority of valves and dampers were decided considering the relations between valve/damper openings and flow rate.

COMPARISON BETWEEN MEASUREMENTS AND SIMULATED RESULTS

In order to evaluate reproducibility of HVACSIM+ Ver.8.1(J), the normal, or non-faulty, state was calculated in the first place at the time step of ten seconds. The items to be evaluated are as follows: the temperature and air flow rate for each zone, the flow rate of supply air, return air and outside air intake of the air handling unit, the temperatures of supply air, outlet water temperature of the cooling coil, chilled water flow rate, and CO_2 concentration of return air.

As each actual data were measured every one minute, all graphs are drawn every one minute hereafter. Comparisons between measurements and the simulated results are shown in Figure 4 to Figure11. The simulated results shown in Figure 4, room temperature, and Figure 5, air flow rate, verify a newly developed type for mixing air between zones, due to temperature difference.

The following are understood from these figures.

a. There are little difference among three values, i.e., measurements and calculated ones with or without air mixing in Figure 5. In Figure 5, however, air flow rate in each zone is better reproduced with the air mixing model compared with otherwise. At ten to twelve hours, the air flow rate of zone 5 with larger cooling load decreases and that of the zone 3 with smaller cooling load grows into more corrective direction due to air mixing driven by temperature difference between zones. Thus, the indoor temperature and flow rate control by VAV unit are fairly reproduced by simulations.

b. As to the room air temperature except for zone 1, reproducibility at cooling down period is not so good. The reason of this is thought to be the effect of thermal storage and it was verified in verification trial for CAV system, too [1][2], and thought to be a sort of limitation for simulations. The temperature of zone 1 well coincides each other, because the set-point was adjusted in order to simulate a specific condition in room partition as described before.

c. As to the air flow rate in each zone in Figure 5, the behavior during a day well coincides each other after introduction of air mixing type. However, the amplitude of oscillation is smaller for simulated results. The reason is thought to be disagreement of time slicing of ten seconds in simulation with that of one second in digital control for VAV dampers.

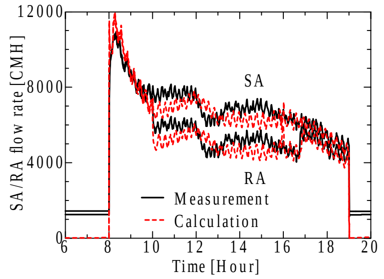

Figure 6 Flow rate of supply / return air (Normal State)

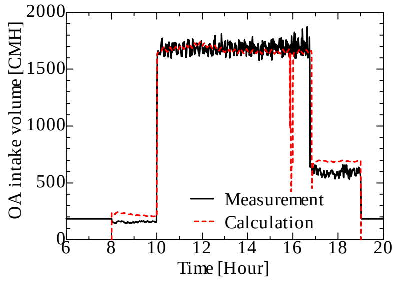

Figure 7 Outside air intake volume (Normal State)

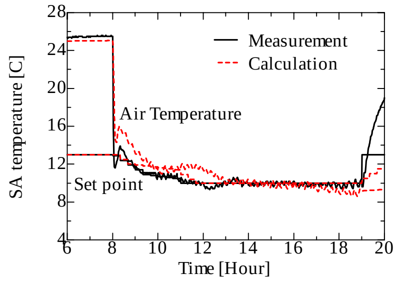

Figure 8 Temperature of supply air (Normal State)

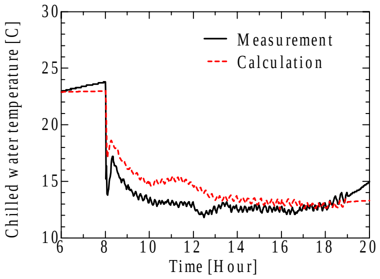

Figure 9 Outlet water temp. of cooling coil (Normal State)

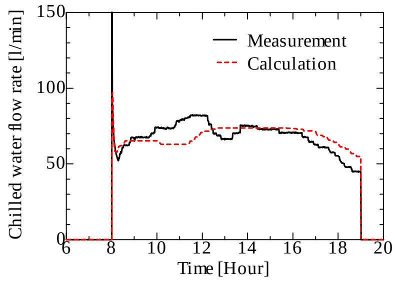

Figure 10 Chilled water flow rate (Normal State)

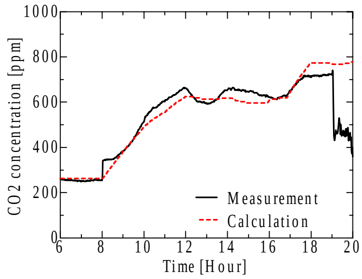

Figure 11 CO_2 concentration of return air (Normal State)

d. The simulated supply and return air flow rate well coincide with measurements as shown in Figure 6. Therefore, It can be said that the fan speed control in VAV system has been well reproduced.

e. As same as the zone flow rate, the oscillation amplitude of outdoor air intake volume for simulated results as shown in Figure 7 is smaller than measurements. It would be because of disagreement of time slicing between simulations and damper control with CO_2 concentration. The momentary error taking place at about sixteen hours is caused by short turn-off of ventilated window fan due to the error in cooling load calculation and the actual.

f. The supply air temperature in Figure 8 and outlet water temperature from cooling coil in Figure 9 have the same kind of errors as the indoor air temperature at cooling down period. This seems natural, because the coil control follows the error corresponding to zone temperatures, which include simulation errors as described above.

g. The measured value of water flow rate in Figure 10 slightly oscillates as same as the supply air flow rate, while the simulated one smoothly changes. The reason will be partly due to the incomplete adjustment of valve characteristics and partly due to the affect of error in zone temperature control.

h. The concentration of CO_2 in Figure 11 fairly well coincides each other between measurements and the simulated, because the number of occupants is almost strictly counted and the outside air intake volume was matched by carefully adjusting the operation of window ventilation fan as described before. The reason why large disagreement occurs after nineteen hours is that calculated CO_2 value maintains constant after the turn-off of air-conditioning as calculation cases, while actually measurement continues and the number of occupants suddenly decreases.

It is now understood that dynamic behavior of the system is well reproduced by simulations from each figure. Therefore, it is considered that HVACSIM+(J) has sufficient reproducibility to simulate the object HVAC system. Besides, the accuracy could have improved more, if some indefinite parameters such as the effective heat capacity of the furniture, fouling factor of the finned coil, moisture multiplier, etc. could have been identified.

Also, if reproducibility of zone temperature improves, the accuracy of reproducibility of the entire system will improve further. The remained important subject is how to introduce air distribution algorithm into the program from the present complete mixing model to incomplete mixing.

APPLICATION TO FAULT SIMULATION

The calculation on the fault state as assumed in Table 6 was carried out as an application to fault simulation. Almost the same parameters were used as in the normal state simulation except for two conditions as follows, which were decided by watching the behavior of the measured results. The set point temperature in zone 1 was adjusted as similarly as at the normal state simulation to meet the actual zone temperature. The drive of the ventilation fan was also adjusted, as same as in the normal case, so that the

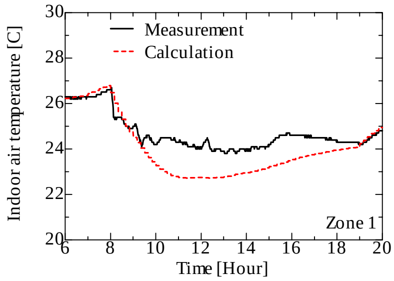

Figure 12-1 Temperature of Zone 1 (Fault State)

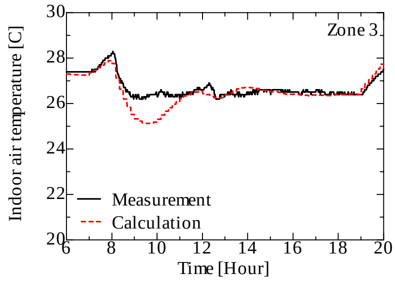

Figure 12-2 Temperature of Zone 3 (Fault State)

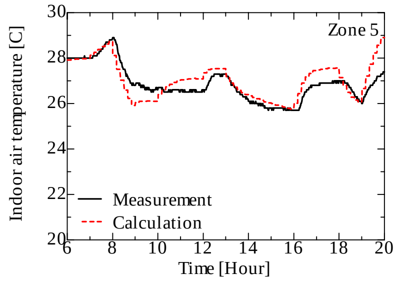

Figure 12-3 Temperature of Zone 5 (Fault State)

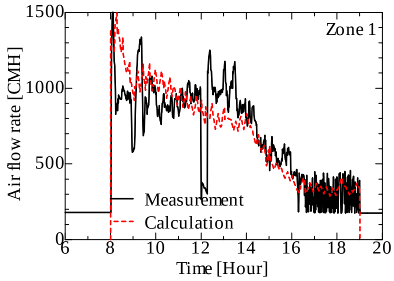

Figure 13-1 Air flow rate of Zone 1 (Fault State)

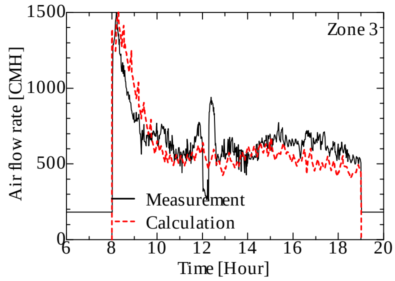

Figure 13-2 Air flow rate of Zone 3 (Fault State)

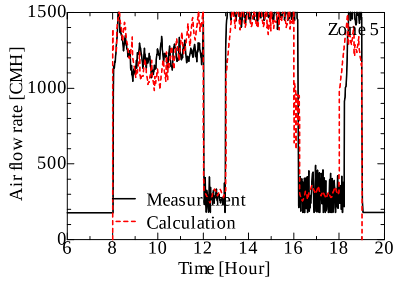

Figure 13-3 Air flow rate of Zone 5 (Fault State)

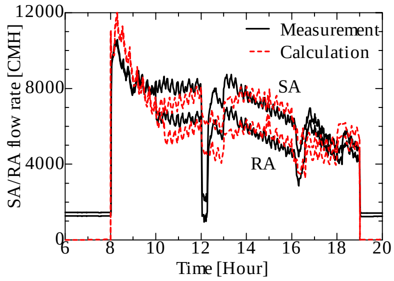

Figure 14 Flow rate of supply / return air (Fault State)

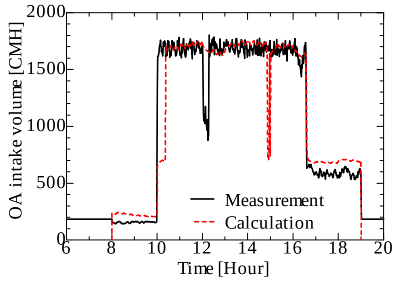

Figure 15 Outside air intake volume (Fault State)

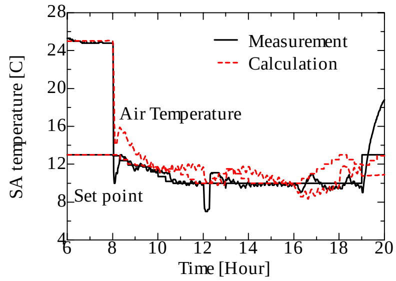

Figure 16 Temperature of supply air (Fault State)

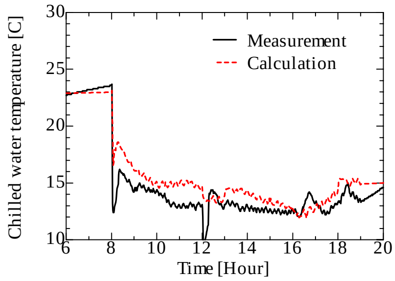

Figure 17 Outlet water temperature of cooling coil (Fault State)

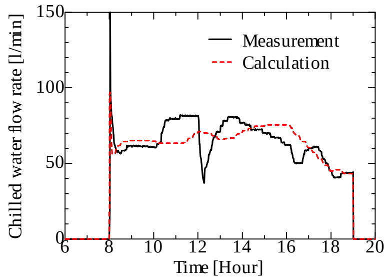

Figure 18 Chilled water flow rate (Fault State)

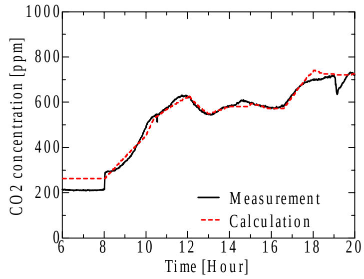

Figure 19 CO_2 concentration of return air (Fault State)

outside air intake volume change agrees with the actual measured values.

The calculated results after above-mentioned consideration are shown in Figure 12 to Figure 19. Similarly with the normal state simulations, the simulated results well coincide with actual measurements for each principal characteristic value of the system, which verify the performance of simulation program. Thus, it is understood that the program can reproduce the temperature and air flow change in zone 5 where a fault state on damper opening was supposed, which is shown in Table 6. Moreover, the phenomena shown in differences between the simulated results and the measurements, for the temperature at cooling down period, oscillation amplitude of air flow rate, and sudden momentary decrease in outside air volume are the same conditions as seen in the normal state simulations.

As to CO_2 concentration, slight error can be found at the time of small flow rate and for the initial value, 200ppm, as shown in Figure 19. As to measured variables around air handling unit at the faulty state, there are the phenomena that supply and return air flow rate, outside air intake volume, supply air temperature, the coil outlet water temperature and chilled water flow rate momentarily decrease at about twelve hours. It is supposed that some disturbances in actual operation during measurements must have taken place while adjusting air flow rate manually to meet the faulty condition.

Except for the slight disagreement observed above, the overall dynamic property are well simulated, therefore, it is expected that HVACSIM+(J) can be used to generate knowledge database for fault detection and diagnosis.

SUMMARY

Authors have verified in the present paper the reproducibility of HVACSIM+(J) by comparing the simulation results and actual measurements for the real HVAC system of a model building, and conclude as follows.

- HVACSIM+(J) is a structural simulation program with the module method, and new element models can be easily built in and it has high applicability.

- The simulation can be executed by obtaining various parameters necessary for calculation from design documents and as-built documents

- To improve reproducibility, it is necessary to decide parameters by investigation, which can not be acquired easily, such as parameters of controllers and cooling coil.

- To establish a good reproducibility by simulation, it is necessary to decide some indefinite parameters like heat capacity of furniture, humidity multiplier, etc. by adjustment.

- HVACSIM+(J) can reproduce dynamic behavior of HVAC systems with high accuracy through the present verification with the real VAV system, if appropriate new modules to represent specific design elements are developed, if parameters of TYPE are correctly identified and adjustment of indefinite parameters are fairly estimated, sometimes by trial and error method, and if the correct values of internal load and weather condition as the boundary data are prepared.

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