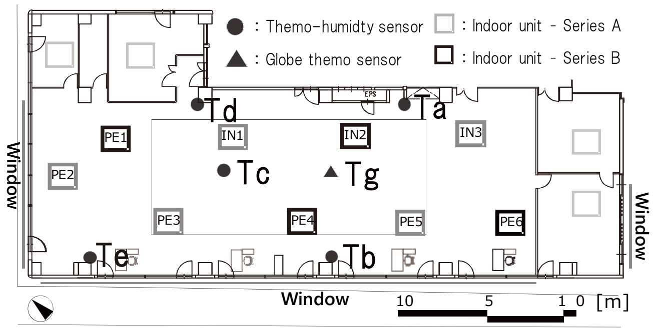

Figure 2. Position of indoor air-cooling unit and measurement points

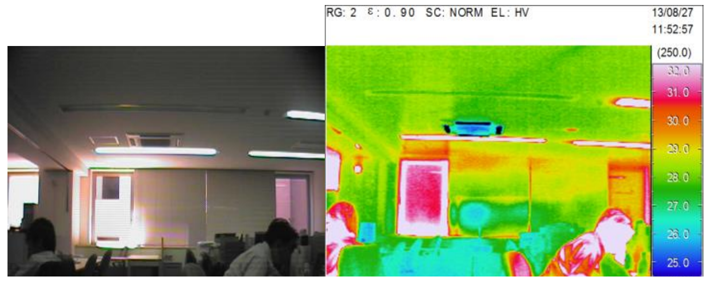

Figure 3. Infrared thermography image of South side

Next the air conditioning control method employed for the present experiments is explained. As shown in Figure 2, the indoor units were alternately grouped to Series A and Series B and each series was controlled separately. Simultaneous operation of Series A and Series B makes 100% operation and the operation of Series A only reduces the operation load by about 50%. Seven driving modes of different operation reduction rates were defined for intermittent operations of each series as shown in Table 2. The AAcC method switches the driving mode to a more energy-saving type when people in the room perform less temperature-adjustment actions and to a less energy-saving type when they perform more temperature-adjustment actions. Therefore, the driving mode changes according to the number of manual switching-on/off actions which are considered as the temperature-adjustment actions of the people in the room.

The present verification experiments used Mode 4 on the first day (July 8) to start the air conditioning of the office. On the next day, the previous day's status information of each indoor unit is analyzed at 0 o'clock to calculate the total number of manual switching-on/off actions of the people. When this total number is in the range from 0 to 74 per day the system changes the mode by one step to the energy-saving side, when in the range from 75 to 150 per day the system maintains the mode, and when it is more than 150 per day the system changes the mode by one step to the less energy-saving side. If no AAcC is made on the previous day, the mode selected on the last day that the control was made is maintained. Therefore, if the previous day is a holiday, the control is conducted in accordance with the control results of the last active air-conditioning controlled day.

THERMAL ENVIRONMENT AND THE RESULTS OF MODE CHANGES OF AIR-CONDITIONING OPERATION

Figure 4 shows the changes of the thermal environment of the office from August 19 to 21 in summer at an outdoor temperature over 30°C. August 19 was the first work day after the summer vacation. The indoor air temperature (hereafter referred to as room temperature) was controlled to be about 28°C with a variation of 2-3°C depending on measurement points, which caused the non-uniform thermal environment. The temperature change by switching on/off the air conditioning was 1-1.5°C on August 20 and 21. In the mode used on August 19, the air conditioning operations were stopped for a prolonged period and hence the temperature variation was expected to be large. However, the actual temperature variation was smaller at each measurement point than the variation on the next day having less energy reduction. This was because the people's temperature adjustment actions corrected the temperature variation. Figure 5 shows the mode change in the AAcC, indoor temperature (average over work hours), and outdoor temperature (in Tokyo) in July. There is no data for holidays, July 26, and August 7 and 27 when the AAcC was not performed. Figure 6 shows the total number of manual switching-on/off actions in a day in the area, except the meeting room, covered by the outdoor unit (1).

The room temperature was maintained at 26-28°C irrespective of the outdoor temperature. On the first day (July 8) of the AAcC, the number of switching-on actions of the people in the room was small, less than 75 per day. Therefore, the air conditioning mode was changed to mode 3 (reduction rate 50%) to save more energy. However, on July 11, the switching-on actions became more frequent and the mode returned to mode 4. On July 16 and 17, the mode was switched successively to mode 1 due to the small number of switching-on actions, and mode 1 was maintained on and after July 18. Since the number of switching-on actions was 151 or more per day on July 31, the mode was changed the next day to mode 2 to reduce the energy saving. The air conditioning mode was selected to be 3 or 4 in early July because of the record-breaking hot weather, but the outdoor temperature decreased in the middle of July and more energy-saving modes were used for the air-conditioning control.

In other words, the AAcC could follow the relatively slow change of the thermal environment caused by the influence from the outside environment.

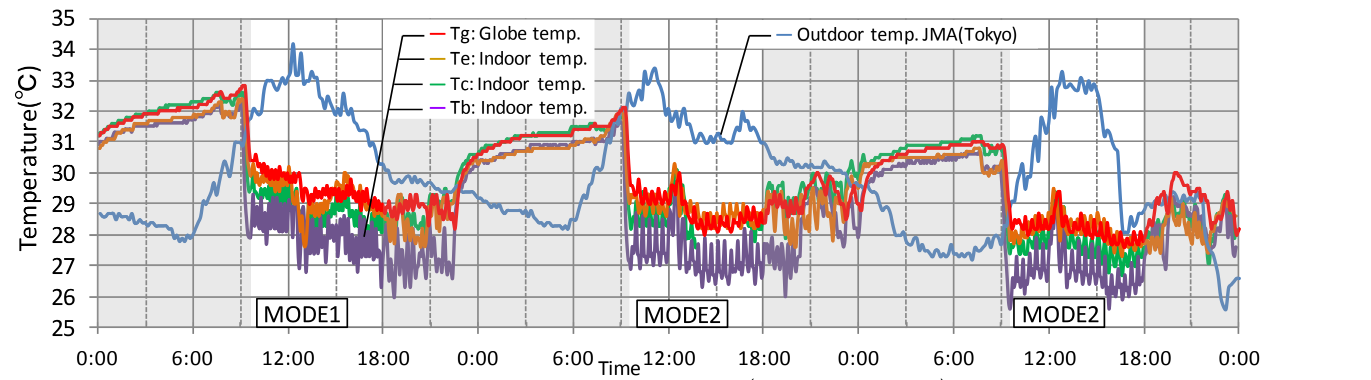

Figure 4. Thermal environment of office (19-21.Aug.2013)

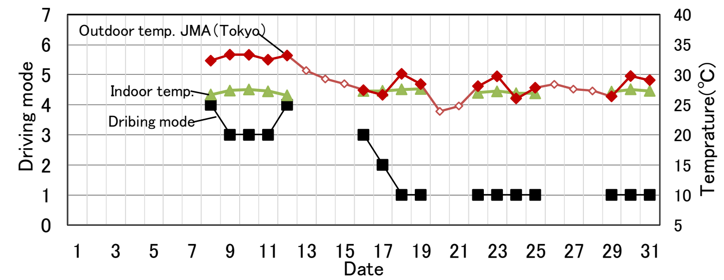

Figure 5. Thermal enviroment and Driving mode of office (Jul.2013)

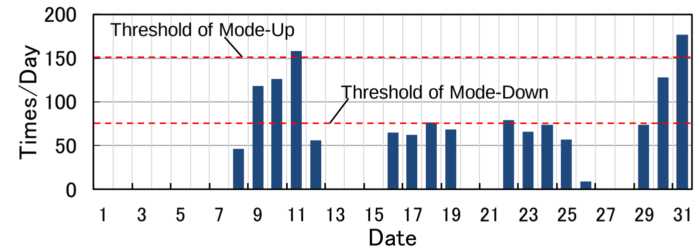

Figure 6. ON/OFF action count (Jul.2013)

DIFFERENCE IN TEMPERATURE ADJUSTMENT ACTIONS IN DIFFERENT PLACES IN OFFICE

Figure 7 shows the total number of manual switching-on/off actions for each indoor unit over July 8 to 31 and August 1 to 31. The switching-on/off actions were more frequent on the perimeter side than on the interior side, and more on the east side than on the west side. This could be because the units on the perimeter side and those on the interior side were operated intermittently in the same mode and hence those on the perimeter side that could be easily affected by the outdoor environment were switched on/off more frequently. Also the number of switching-on/off actions was not the same for the indoor units on the perimeter side or for the units on the interior side. This could be because of the non-uniform thermal environment, difference in the each person's position, attribution, thermal sensation, comfort, and psychological conditions.

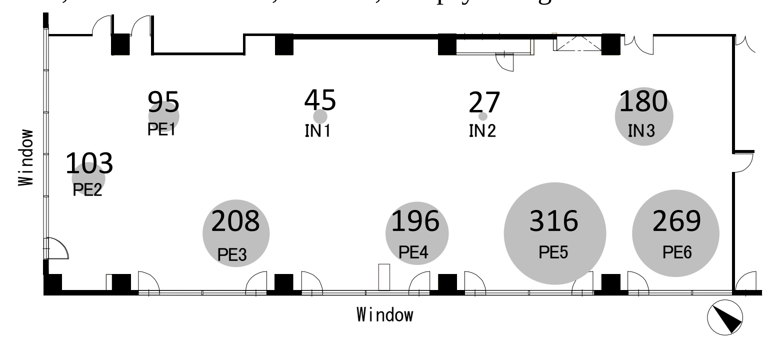

Figure 7. Count of switch every indoor unit (Jul.2013)

RESULTS OF INDOOR UNIT OPERATION SUPPRESSION AND ENERGY CONSUMPTION REDUCTION

Table 3 shows the expected reduction rate[Note1)] of the intermittent operations and the actual reduction rate calculated from the actual air conditioning operation hours.

The reduction rate difference [%]= Expected reduction rate [%] – actual reduction rate [%] in each mode

Table 3 Reduction rate of A/C indoor unit of office area

Month	Days of Auto Control (day)	Estimated Rate (%)	Usage of Room (h)	Usage of A/C (h)	Run. Rate of A/C (%)	Reduction Rate of A/C (%)	Outdoor Temp. JMA(Tokyo) (°C)
Jul.	11	64.4	82.5	38.4	46.6	53.4	27.3
Aug.	15	60.5	112.5	57.1	50.8	49.2	29.2
Sep.	19	65.8	142.5	60.0	42.1	57.9	25.2

The air conditioning driving mode changed every day according to the feedback from the people's temperature adjustment behaviors. The mode change in July, August and September when the AAcC was conducted was recorded. The data in the first week of July were omitted since this was the period for the AAcC to meet the condition As a result of the measurement, the expected reduction rate in July was 66.4% and the actual reduction rate was 53.4%, smaller than the expected rate due to the people's temperature adjustment. The expected reduction rate and the actual reduction rate were both smaller in August than in July but larger in September. This could be because the outdoor temperature in August was high and that in September was lower than in July and August. Since the difference between the expected and actual reduction rates was 7.9-11.3%, one can see that the people's temperature adjustment actions changed the mode by 1 step and the office was controlled in this mode range. To reduce this difference, the threshold (total number of manual switching-on/off actions) of the mode switching to higher energy consumption should be set to a small value. However, this may cause excessive air conditioning with higher energy consumption. It is therefore important to select an appropriate threshold.

Table 4 shows the comparison with the power consumption in 2010 when the air conditioners were kept switched on at 28°C. The energy consumption of each air conditioner was not measured in 2010 but the total consumed energy and the working hours of the indoor units were measured. The power consumption of the indoor and outdoor units was estimated from these measurements[Note2)]. The total consumption energy of the air conditioning estimated from each of the units was 11,945kwh, about 4% deviated from the actual measurement value 12,402kwh, indicating that the estimation was effective. It is concluded from this result that the energy consumption in the office room in 2013 was reduced by 46% in 2010 by the AAcC. The outdoor temperature was lower by 0.7°C in July, 0.4°C in August, and 0.1°C in September than in the same months in 2010. However, the influence of this difference is small since the change in the energy consumption of the outdoor unit due to the outdoor temperature change is 180.1kwh/month-°C. The office was used for 58 days in July, August and September both in 2010 and 2013. Although the number of people decreased by 10%, the use condition was almost the same in both years.

Table 4 Power reduction result (Jul.-Sep. 2013 vs Jul.-Sep. 2010)

Division	Control method	Jul.-Sep. 2013 Active air-conditioning control	Jul.-Sep. 2010 Temperature-constant control (28°C)		Reduction rate
		Measured	Measured	Estimated*	
Outdoor unit(1) (office area)					
	Indoor unit working time (h)	3420	6374	-	
	Detail: Office area (9unit) (h)	2788	5631		50%
	Detail: Other (4unit) (h)	632	743		15%
	Indoor unit (kWh)	256		476	
	Outdoor unit (kWh)	4118		7676	
	Power consumption (kWh)	4374		8152	46%
Outdoor unit(2) (Meeting room area)					
	Indoor unit working time (h)	1476	3866	-	62%
	Power consumption (kWh)	1448		3793	62%
Total					
	Air-conditioning electric power consumption (kWh)	5822	12402	11945	53%

* The estimated values of each electric consumption is estimated from indoor unit working time of 2010 based on air-conditioning electric consumption per indoor unit working time of 2013.

The above facts indicate that the major causes for the energy consumption reduction were the suppression of the air conditioning operations during the office hours as shown in Table 3, and prevention of forgetting to stop the air conditioners after office hours or unnecessary operation of them by the automatic termination of the air conditioners after office hours, which had been controlled manually.

CONCLUSION

In this study, an active air-conditioning control (AAcC) system was introduced to an office room where there were multiple indoor air-conditioning units and analyzed based on verification experiments conducted in summer with the focus on the thermal environment and the temperature adjustment actions of people in the room. By incorporating occupants' switching on/off action into the system, this control method enables the automatic control of air-conditioning along with the thermal comfort request of occupants. Major results are as follows.

1) The AAcC was conducted at a preset temperature of 26°C in an office room with multiple indoor units, which were alternately grouped into two. After the air conditioning mode is stabilized, the mean room temperature was maintained at 26-28°C irrespective of the outdoor temperature. The temperature variation at the sensor positions due to the start-stop operations of the indoor units was 1-1.5°C and the room temperature variation across the office room was about 2-3°C.
2) The air conditioning operation reduction rate for the office room was 53.4% in July, 49.2% in August, and 57.9% in September.
3) The results indicated that the AAcC of the office area in 2013 reduced the energy consumption by 46% from the consumption in 2010. The major causes for the large reduction are the suppression of the operation of the air conditioners during the office hours and the prevention of forgetting to stop the air conditioners after office hours.
4) The number of manual switching-on/off actions varied from place to place in the room and differed between the perimeter side and the interior side. It was therefore found that people's preference on the thermal environment could be deduced from their air conditioner adjustment actions.
5) In the air-conditioning control according to the number of people's switching-on/off actions, the AAcC could follow a change in the thermal environment caused by the influence of the outdoor temperature.

The above results showed that the AAcC based on the number of people's air conditioner adjustment actions realized air-conditioning control appropriate to the thermal environment of an office room with multiple air conditioners.Since the number of switching-on/off actions was counted every day, the system could follow only a slow thermal environmental change over two or more days. It was also clarified that holidays needed to be taken into consideration. Also, each indoor unit should be controlled separately to compensate for the variation of the thermal environment across the room.

The change-following performance should be improved by using a shorter period of the feedback from the number of manual switching-on/off actions in people's temperature adjustment behavior or by using the weather forecast data, and a system of applying the AAcC to each of the indoor units separately.

Note 1) The expected reduction rate was calculated from expected working hours of the air conditioners in office hours (7.5h). The expected working hours of the air conditioners were given by summing up the expected working hours calculated from every day's air conditioning modes.

Note 2) The power consumption per operating hour of indoor units, that of outdoor units, and that of air conditioners is calculated from the measurement results in 2013 (July to September) and from the total working hours of indoor units in 2010. Since the specifications of the indoor and outdoor units are different in the office area and in the meeting room area, the power consumption was calculated separately for each of the areas.

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