EVALUATION AND OPTIMIZATION OF AIR-CONDITIONER ENERGY SAVING CONTROL CONSIDERING INDOOR THERMAL COMFORT

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ABSTRACT

For the purpose of reducing the room air-conditioners' energy consumption, an energy saving control method is proposed formerly. In this paper its energy saving effect is confirmed through experiments conducted in six office rooms in actual use. The experiment results show that the air-conditioners controlled by the present energy saving control logic and parameter settings can save electric power up to 3.0% compared to ordinary control. Further, if the energy saving control parameters of room temperature set points are fixed at 27^{o}C for cooling operation in summer and at 23^{o}C for heating operation in winter, in average 18.7% and 23.8% electric power can be saved. At the same time, in order to check whether the indoor air temperature of 27^{o}C in summer and 23^{o}C in winter will cause uncomfortable complaints or not, questionnaires on indoor thermal comfort and sensation are conducted. The results show that these indoor temperatures are acceptable for the occupants. Finally a room model and the air-conditioner control model are developed to simulate the performance of one-minute interval room air temperature, which is used to determine on/off status of air-conditioners for the purpose of calculating electric power consumptions. The models finally are used to find out the optimal control parameter settings. The results show that the operation at optimal control set points can save 28.9% energy compared to the ordinary operation.

KEYWORDS

Optimization, Electric power consumption, Thermal comfort, Air-conditioner, Energy saving control

INTRODUCTION

Energy issue becomes important since the Energy Crisis caused by the Middle East War in 1973 to 1974, which led to the establishment of International Energy Agency (IEA) (Scott 1994). Further, energy issue is turning to be more important accompanying the increasing aggravation of global warming. Less energy consumption implies less emission of green house gas and less impact on global environment. Thus the researches on energy conservation are conducted in all kinds of field. In the field of building, one third of primary energy is consumed in non-industrial buildings where it is utilized for space heating and cooling, lighting and the operation of appliances (ECBCS 2009). Therefore a lot of efforts on building energy conservation are tried, such as improve thermal insulation of building envelopes, develop new type building envelope, develop energy efficient heating/cooling equipments, and improve building commissioning etc. Among the researches on building energy conservation, researches on saving the energy consumed by air-conditioning system hold a majority because air-conditioning systems account for one third to half of total building energy consumption. Further, air-conditioning systems are so complicated that energy is easy to be used inefficiently and there is large potential to improve the energy efficiency. Regarding the energy conservation of air-conditioner, many researches focus on developing new energy efficient equipments (Chen et al. 2008, Maheshwari et al. 1991, Yang and Lee 2001) or new energy efficient system (Atthajariyakul et al. 2008, Chow et al. 2006, Ghaddar et al. 2003). Ahmed et al. (2007) developed a fuzzy logic to save energy for a central air conditioning system. Yamamoto and Abe (1994) concluded the air temperature set point of computer room can be raised to 28^{o}C without cause any uncomfortable conditions. Chiou et al. (2008) used experiment to study the energy saving of air-conditioners when forced downtime strategy is implemented. But how to decide the downtime is not studied. Therefore the authors proposed a method to decide forced thermo-off time using weather forecast temperature and humidity of the present day (Hashimoto et al. 2008). The forced thermo-off command is sent from command center to all remote air conditioners. The energy saving effects is confirmed to be 7% ~27% at a university campus in the summer of 2007. But the heating operation in winter, influence of the temperature rise caused by forced thermo-off to occupants, and the optimal thermo-off time is not yet studied.

For the purpose of clarifying these issues, the following three steps of research are conducted. 1) Experiments of the energy saving control being implemented and not implemented are conducted. Detailed indoor and outdoor air temperature and humidity and air-conditioners power consumption are measured. 2) Questionnaires on indoor thermal comfort are conducted during the experiment period. 3) Finally, optimization is conducted using simulation to find out the optimal control parameter, i.e. the forced thermo-off time.

CONCEPT OF THE ENERGY SAVING CONTROL

The concept of energy saving control is to force an air-conditioner off for a certain period and to limit the compressor inverter output to reduce the cooling or heating capacity for the purpose of preventing overcooling or overheating. For the multi-indoor-unit air-conditioners (MIAC), both forced thermo-off and capacity limitation control are available. But for the single-indoor-unit air-conditioners (SIAC), only forced thermo-off control is available because they are small and simple. The forced thermo-off time and capacity limitation are decided according to the Discomfort Index (DI) calculated using the weather forecast temperature and humidity of the present day, as shown in Equation 1 (Bosen and Thom 1959). The forced thermo-off time and capacity limitation vs. DI are shown in Table 1. Further, the air temperature set points set by room occupants are periodically reset to a recommended value for the purpose of preventing unreasonable temperature setting. The remote control center decides the forced thermo-off time according to the weather forecasts for the location where an air-conditioner exists. The control command of forced thermo-off time and temperature setting are sent to all local air-conditioners once a day.

$$DI = 0.81T_o + W_o(0.99T - 14.3) + 46.3 \qquad (1)$$

EXPERIMENTS

The following three type experiments are conducted in the winter of 2007 and summer of 2008 at six office rooms in the authors' university. One of the six rooms is a large one with the floor area of 194 m^2 and equipped with a MIAC. The other five rooms are small with the floor area of 81 m^2 and equipped with two SIACs.

1) Ordinary operation (OP)

This operation is to control air-conditioners thermo-on or thermo-off according to temperature set point and room air temperature. Indoor air-temperature set points are decided by room occupants freely. Almost all air-conditioners are controlled by this method, so it is named ordinary operation.

2) Energy saving operation (ES)

This operation is to apply the proposed control logic to the ordinary operation, i.e. air-conditioners are controlled thermo-on or thermo-off according to temperature set point and room air temperature and further are forced off during the predetermined thermo-off time.

3) Energy saving operation and temperature set point reset (ES&TS)

This operation is to reset the temperature set point to the recommended temperature set points besides the

Table 1 Forced thermo-off time and capacity limitation vs. DI

DI	Percent of thermo-off time in one hour	Percent of inverter output
<38	0%	0%
38 ~ 39	0%	70%
39 ~ 42.5	0%	40%
42.5 ~ 45	20%	40%
45 ~ 48	30%	40%
48 ~ 71	40%	40%
71 ~ 74	30%	40%
74 ~ 77	20%	40%
77 ~ 80	10%	40%
80 ~ 83	0%	40%
83 ~ 84	0%	70%
>84	0%	0%

Table 2Experiment schedule of operating Air-conditioners

	Mon.	Tus.	Wed.	Thu.	Fri.	Sat.	Sun.
	14	15	16	17	18	19	20
Jan.	21	22	23	24	25	26	27
	28	29	30	31			
					1	2	3
	4	5	6	7	8	9	10
Feb.	11	12	13	14	15	16	17
	18	19	20	21	22	23	24
	25	26	27	28	29		
						1	2
	3	4	5	6	7	8	9
	10	11	12	13	14	15	16
Mar.	17	18	19	20	21	22	23
	24	25	26	27	28	29	30
	31						
Apr.		1	2	3	4	5	6

	Mon.	Tus.	Wed.	Thu.	Fri.	Sat.	Sun.
					1	2	3
	4	5	6	7	8	9	10
Aug.	11	12	13	14	15	16	17
	18	19	20	21	22	23	24
	25	26	27	28	29	30	31
	1	2	3	4	5	6	7
	8	9	10	11	12	13	14
Sep.	15	16	17	18	19	20	21
	22	23	24	25	26	27	28
	29	30					
			1	2	3	4	5
	6	7	8	9	10	11	12
Oct.	13	14	15	16	17	18	19
	21	21	22	23	24	25	26
	27	28	29	30	31		

Legend:
- Odinary operation
- Energy saving operation
- Energy saving + set point (23°C for winter, 27 °C for summer)
- Energy saving + set point (24°C for winter, 28 °C for summer)
- Questionnair
- Red letter Holiday

energy saving control. Two recommended temperature set points, which are 27°C and 28°C for summer and 22°C and 23°C for winter, are used in this experiment.

The four operation modes, i.e. OP, ES, ES&TS27/22, ES&TS28/23, are implemented with a daily alternation. The detailed operation schedule is shown in Table 2.

During the experiment period, the weather data, indoor air temperature and humidity, air-conditioner running data are measured with one minute interval. The detailed measurement items and instruments are shown in Table 3.

Comparison of energy consumption

The measured data of all the rooms are averaged for the purpose of checking the general performance of the proposed energy saving control method. The average indoor air temperatures, outdoor air temperatures, and hourly summed electric power consumptions are compared. Further, energy saving ratio of energy saving operation to ordinary operation are calculated as well. The power consumptions and temperatures of cooling operation in summer and heating operation in winter are shown in Figure 1 (Data of ES&TS22 are lost and not shown).

For cooling operation in summer, the ordinary operation and energy saving operation have similar average outdoor temperatures of 27.3 and 26.9°C, similar indoor temperature of 26.1 and 26.2°C, and similar hourly power consumption of 0.407 and 0.413 kWh. If the energy saving method plus the room temperature set point reset to 27°C and 28°C is

Table 3 Measurement items

Measurement item		Instrument
Weather data	Temperature	Weather monitoring system
	Humidity	
	Direct Solar radiation	
	Global radiation	
	Wind speed	
	Wind direction	
Indoor thermal environment	Temperature	Temperature/humidity recorder
	Humidity	
	Radiation temperature	Globe thermometer
Air-conditioner running data	Power consumption	Clamp power meter
	Inlet and outlet air temperature	Thermal couple
	Inlet and outlet air humidity	Temperature/humidity recorder
	Air flow rate of indoor unit	Multi-channel anemometer
	On/off status	Air-conditioner running data recorder
	Temperature set point	
	Condensing pressure	
	Evaporation pressure	

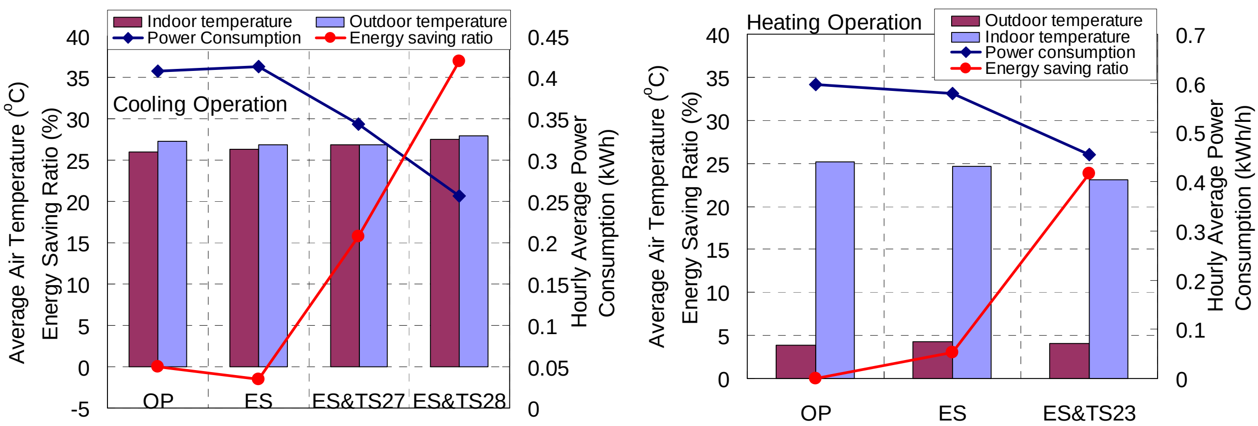

Figure 1 Power consumption of different operation control (left: cooling operation, right: heating operation)

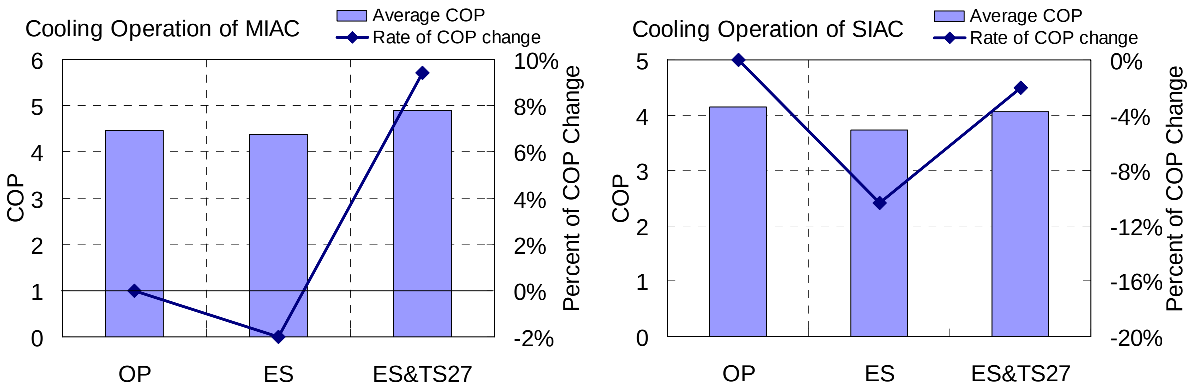

Figure 2 Comparison of COPs at different operation control method (left: MIAC, right: SIAC)

implemented, the energy saving ratios can be 18.7% and 35.3% respectively.

For heating operation in winter, the ordinary operation and energy saving operation have similar average outdoor temperatures of 3.9 to 4.3°C and similar indoor temperature of 25.1 and 24.7°C, while the ES operation save energy by 3% in average. Further, if the energy saving method plus the room temperature set point reset to 23°C is implemented, the energy saving ratio can be increased to 23.8%.

Comparison of Coefficient of Performance (COP)

Besides energy consumption, energy efficiency is compared as well. The comparison of coefficient of performance (COP, a dimensionless value of cooling or heating production to power consumption) of MIAC and SIAC is shown in Figure 2. The energy saving control caused COP to drop by 2% for MIAC and 10.4% for SIAC. The reason for this COP drop is considered to be the forced on/off. Because after the period of the air-conditioner being forced off, the cooling/heating load becomes higher for the thermal accumulation or loss, the air-conditioner's compressor will run at higher rotational speed for the air-conditioner equipped with a variable speed drive. When an air-conditioner is running at high rotational speed, comparing to running at low rotational speed, the ratio of area of evaporator and condenser to cooling/heating production is smaller, so it needs more energy to produce required heat, i.e. COP is lower. Although the forced thermo-off will cause instant COP drop, the summed energy consumption will decrease because forced thermo-off leads to shorter running time as well.

QUESTIONNAIRE

Although increasing the cooling temperature setting to higher values for cooling operation and decreasing the heating temperature setting to lower values for heating operation can achieve large energy saving, the high indoor temperature in summer and low indoor temperature in winter might influence the comfort level and productive of room occupants. So for the purpose of checking the influence of the energy saving operation to the occupants, questionnaires on thermal comfort and sensation are conducted during the experiment period.

Thermal comfort was asked using 4-point scale and thermal sensation was asked using 7-point scale, as shown in Table 4.

The average thermal comfort and sensation of six

Table 4 Thermal comfort and sensation scale

Number	Thermal comfort	Thermal sensation
1	Comfortable	Cold
2	Slightly comfortable	Cool
3	Uncomfortable	Slightly cool
4	Very uncomfortable	Neutral
5	-	Slightly warm
6	-	Warm
7	-	Hot

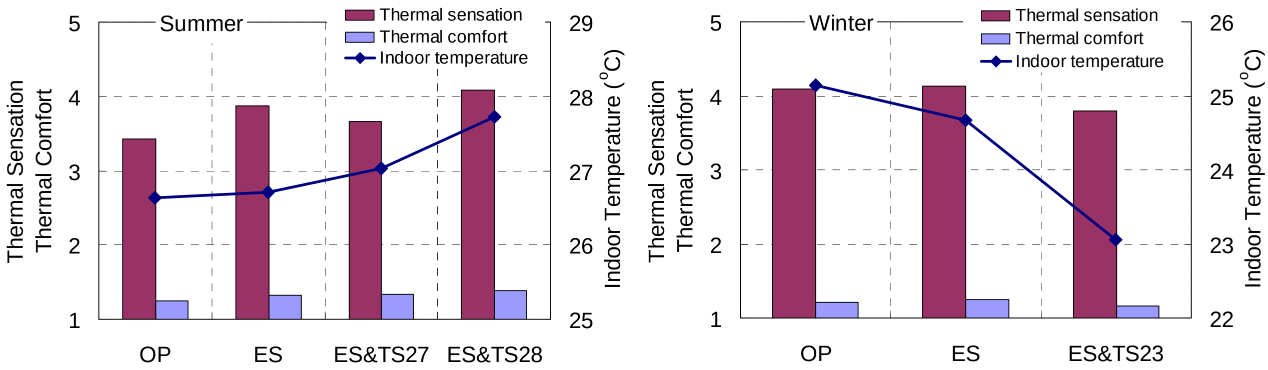

Figure 3 Comparison of thermal comfort and sensation (left: summer, right: winter)

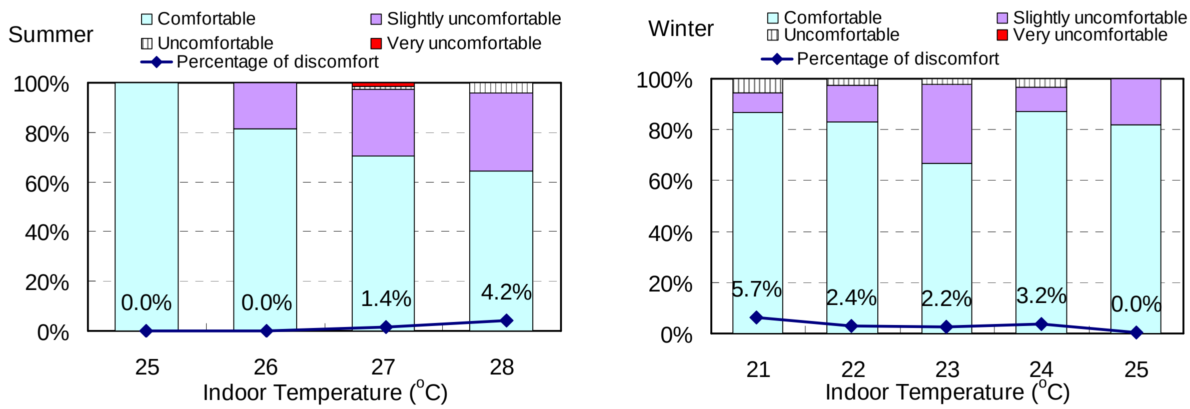

Figure 4 Percentage of thermal comfort at different indoor temperature (left: summer, right: winter)

rooms at different operation method are shown in Figure 3.

For cooling operation in summer, average thermal comfort for the three-type operations is 1.3 to 1.4, and the average thermal sensation is 3.4 to 4.1, which show that all the operation method can prove comfortable thermal environment. Further, the average thermal sensation for ordinary operation is 3.4, which is 0.6 lower than the neutral point of 4 and shows that the ordinary operation tends to overcool the indoor environment. To prevent overcooling is the purpose of the proposed energy saving control.

For heating operation in winter, average thermal comfort for the three-type operations is around 1.2, and the average thermal sensation is 3.8 to 4.1, which show that all the operation method can prove comfortable thermal environment. The thermal environment provide by all the three-type heating operation in winter is closer to comfort and neutral sensation than that of cooling operation in summer.

Further, the detailed percentages of the 4-point thermal comfort and percentages of discomfort (the percentage of voting for "uncomfortable" and "very uncomfortable") at different indoor temperature are shown in Figure 4. For cooling operation, when indoor temperature is within the range of 25^{o}C to 28^{o}C, the discomfort percentage is less than 5%. For heating operation, when indoor temperature is within the range of 21^{o}C to 25^{o}C, the discomfort percentage is no more than 6%. The reason why this relatively high indoor temperature in summer and low temperature in winter did not cause large discomfort ratio is considered to be the occupants adapt themselves to the thermal environment by adjusting their clothes. The occupants' typical clothes for summer were short-sleeved shirt and jeans with the average thermal insulation value of 0.45clo, and those for winter were thick sweater and jeans with the average thermal insulation value of 0.92clo. This results show that the indoor temperature set point can be set as high as 28^{o}C in summer and as low as 21^{o}C in winter with uncomfortable complaint less than 6% if occupants can take adaptive comfort measures.

OPTIMIZATION OF ENERGY SAVING CONTROL

The present energy saving control settings, i.e. capacity limitation ratio and forced thermo-off time, are decided by the authors empirically. They might not be the optimal. Therefore the optimization for forced thermo-off time is studied. The optimization for capacity limitation ratio is under developing.

Optimization problem

The objective of this optimization problem is to find the minimum energy consumption, as shown in Equation 2.

$$\min \sum_{t=1}^{N} E_t \qquad (2)$$

The objective function is the seasonal total energy consumption, which is calculated using simulation at different control settings. The variable is control setting, i.e. forced thermo-off time.

Simulation method

For the purpose of obtaining the energy consumption of air-conditioners, the following three-kind models are needed.

1) One-minute interval indoor air temperature simulation model

In order to obtain an air-conditioner's energy consumption, its status of on or off needs to be known. Therefore at least one-minute interval indoor air temperature is necessary to determine an air-conditioner's status of thermo-on or thermo-off by comparing the indoor air temperature to the temperature set point. The one-minute interval indoor air temperature is simulated using response factor method (Wang et al. 2006).

2) Air-conditioner model

This model is to simulate the energy consumption of an air-conditioner given indoor and outdoor temperature and humidity. In this paper, the regression model fitted using manufacturers' specification data is used (Wang et al. 2005).

3) On/off control model

This model is to determine the on/off status of an air-conditioner by comparing the indoor air temperature to the temperature set point and applying the forced thermo-off control logic.

Simulation validation

The simulation is validated by comparing the simulated room air temperatures and power consumptions to measured ones. For validation, the inputs to the simulation models are building and weather information, air-conditioner information, and measured data of indoor air temperature, temperature set point, cooling/heating production, and power consumption. The outputs of the simulation are indoor air temperature and humidity, and power consumption. The simulation flow for validation is shown in Figure 5.

The validation results are shown in Figure 6. The Mean Bias Error (MBE) and Root Mean Square Error (RMSE) of indoor air temperature simulation are 0.7^{o}C and 1.3^{o}C, which shows that the temperature simulation is accurate enough for studying the performance of on/off control. Regarding the power consumption, the sum of measured power is 15.9% more than the simulated one. This result implies that the actual machine performance is 15.9% worse than the specification performance. For the purpose of simulating the actual machine performance, the simulated power consumptions are multiplied by a compensation coefficient of 1.159.

Optimization

The optimization flow is shown in Figure 7. Different to the simulation validation, measured data are not input to optimization models. The input data are only building and weather information. By changing the forced thermo-off time and comparing the room temperature to set point, the on/off control model determine the on/off status of an air-conditioner. Then the on/off status is used by air-conditioner model to simulate cooling/heating production and power consumption. Then the cooling/heating production is input to room temperature simulation model to obtain the one-minute interval indoor air temperature and humidity. The simulated indoor temperature is input to on/off control model to determine the on/off status for the next time step.

The optimal forced thermo-off time is searched using the simplex search method (Lagarias et. al. 1998) in the range of 0.1 to 0.9.

The optimization results are shown in Figure 8. The

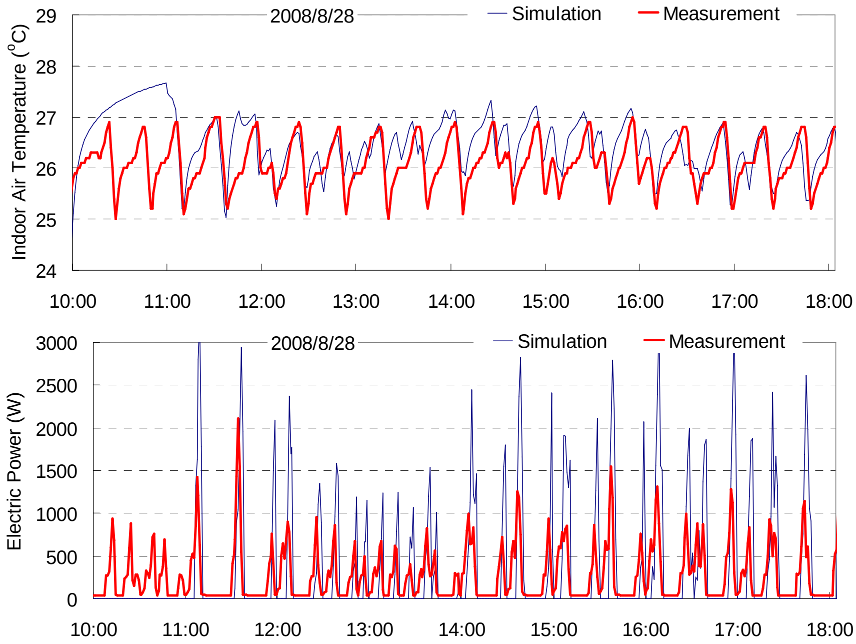

Figure 6 Simulation validation results

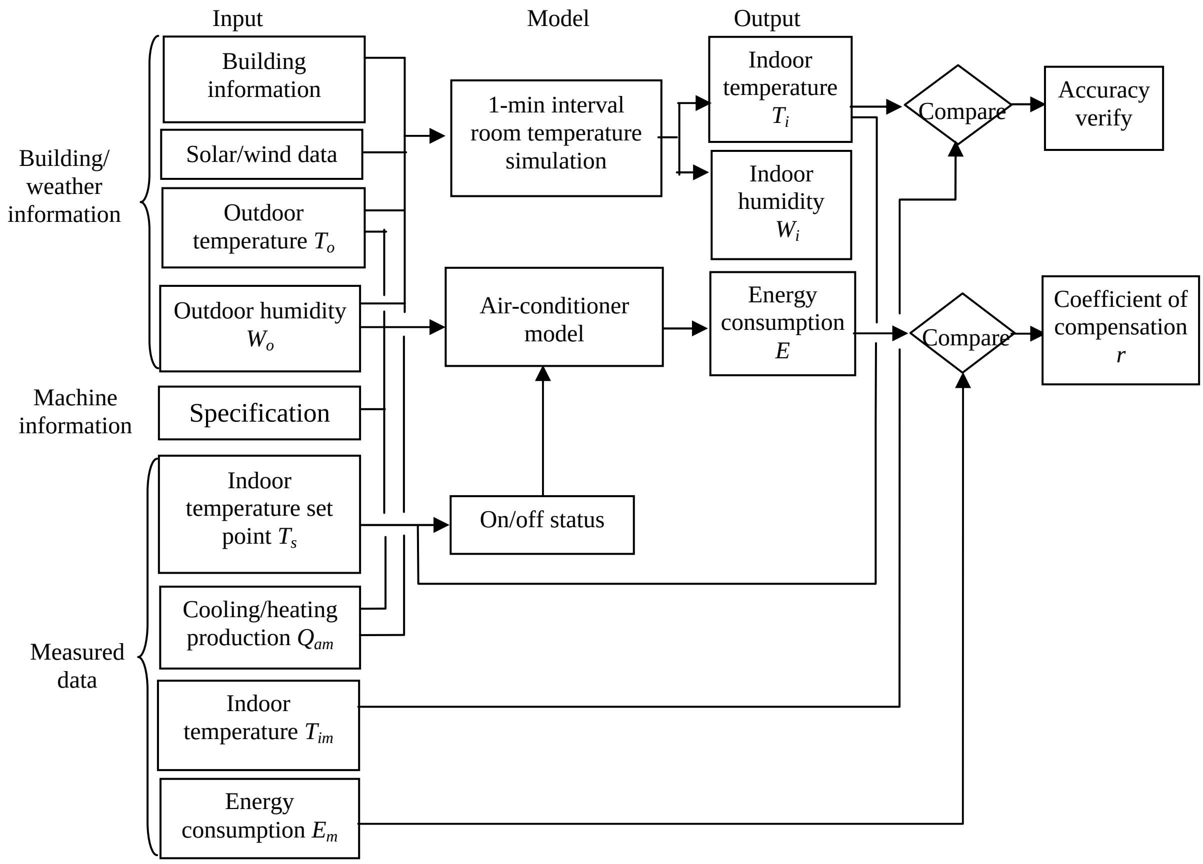

Figure 5 Flow chart of simulation validation

simulated indoor air temperatures and power consumptions of the optimal control setting, present control setting and ordinary operation are compared. The indoor temperature simulation results show that the optimal control frequently let room temperature reach 28°C. This high indoor temperature can lead to large amount of energy saving with very few uncomfortable complaints (less than 5%). The simulation results of power consumption show that the optimal control can save 28.9% energy compared

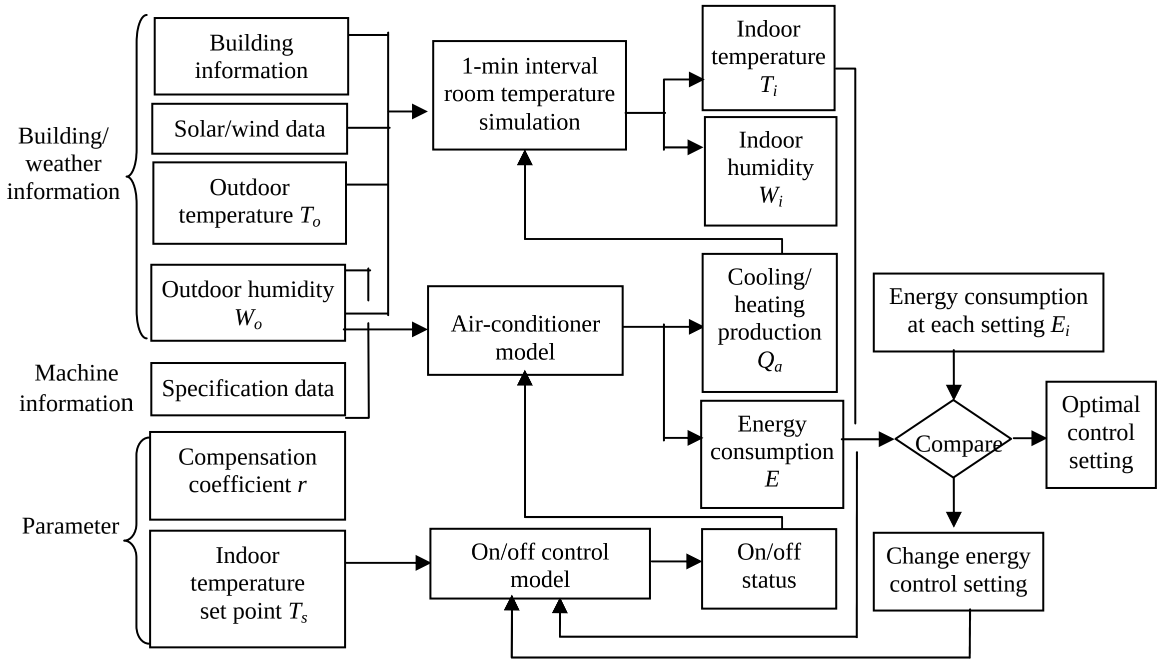

Figure 7 Flow chart of optimizing the control setting of forced thermo-off

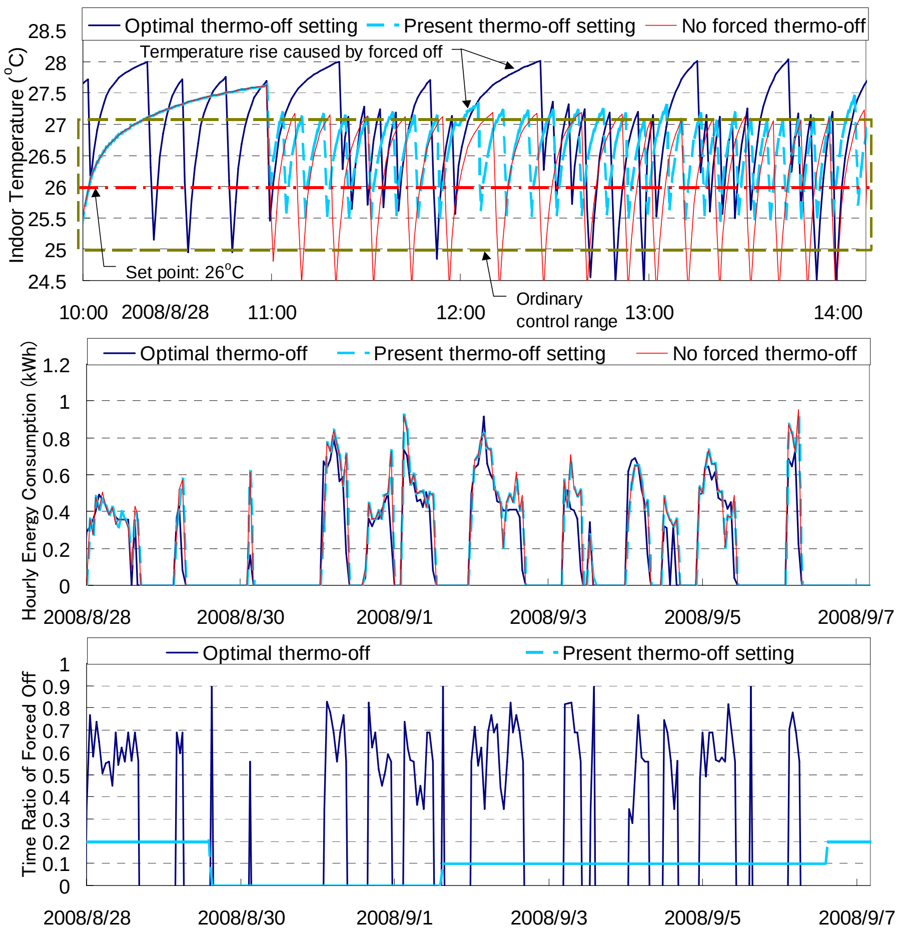

Figure 8 Comparison of optimized control to ordinary control

to the ordinary operation. The present control setting can only save 6.5% energy because the force thermo-off control is too moderate.

CONCLUSIONS

Three-type of experiments are conducted to verify the energy performance of a proposed energy saving control method. The present energy saving control setting does not lead to energy saving in cooling operation but can save 3.0% energy for heating operation. Further, when the indoor air temperature set point is set at a high level of 27°C for cooling operation and a low level of 23°C for heating operation, the energy saving rate is 18.7% and 23.8% respectively. Questionnaires on indoor thermal comfort and sensation are conducted as well. The results show that when indoor air temperature is 27°C and 28°C in summer, the percentage of uncomfortable vote is 2.7% and 4.2% respectively. When indoor air temperature is 23°C and 22°C in winter, the percentage of uncomfortable vote is 2.2% and 2.4% respectively. This result implies that the indoor temperatures of 27°C and 28°C in summer and 23°C and 22°C in winter are acceptable for the occupants. Finally simulation is used to find out the optimal control parameter. The results show that the operation at optimal control can save 28.9% energy compared to the ordinary operation.

REFERENCES

Ahmed S.S., Majid M.S., Novia H., Rahman, H.A., 2007, Fuzzy logic based energy saving technique for a central air conditioning system, Energy, Vol. 32, Issue 7, pp. 1222-1234

Atthajariyakul S., Lertsatittanakorn C., 2008, Small fan assisted air conditioner for thermal comfort and energy saving in Thailand, Energy Conservation and Management, Vol. 49, Issue 10, pp. 2499-2504

Bonneville Power Administration, 1992, Building Commissioning Guidelines, p iii.

Bosen, J.F., Thom, E.C., 1959, The discomfort index, Weatherwise, April, 1959

Chen H., Lee W.L., Ylk F.W.H., 2008, Applying water cooled air conditioners in residential buildings in Hong Kong, Conservation and Management, Vol. 49, Issue 6, pp. 1416-1423

Chiou C.B., Chiou C.H., Chu C.M., Lin S.L., 2008, The study of energy-saving strategy for direct expansion air conditioning system, Energy and Building, Vol. 40, Issue 9, pp. 1660-1665

Chow, T.T., Fong, K.F., Chan, A.L.S., Lin, Z., 2006, Potential application of a centralized solar water-heating system for a high-rise residential building in Hong Kong, Applied Energy, Vol. 83, Issue 1, pp. 42-54

ECBCS, 2009, http://www.ecbcs.org/home.htm, accessed 2009.2

Ghaddar N., Ghali K., Najm A., 2003, Use of desiccant dehumidification to improve energy utilization in air-conditioning systems in Beirut, International Journal of Energy Research, Vol. 27, Issue 15, pp. 1317-1338

Hashimoto s., Matsuda T., Shinbayashi H., Yoshida H., Wang F., Shiota K., 2008, An energy-saving method for air-conditioning system by using weather forecast, Proceedings of Conference: Air Conditioning and the Low Carbon Cooling Challenge, Windsor, UK, Paper No. 5.

Lagarias J.C., Reeds J. A., Wright M. H., and Wright P. E., 1998, Convergence Properties of the Nelder-Mead Simplex Method in Low Dimensions, SIAM Journal of Optimization, Vol. 9 Number 1, pp. 112-147.

Maheshwari G.P., Al-Ragom F., Suri R.K., 2001, Energy-saving potential of an indirect evaporative cooler, Applied Energy, Vol. 69, Issue 1, pp.69-76

Scott, R., 1994, The History of the International Energy Agency, the First Twenty Years, Volume I, Origins and Structure, Paris, International Energy Agency.

Yamamoto M., Abe T., 1994, The new energy saving way achieved by changing computer culture, IEEE Transactions on Power System, Vol. 9 Issue 3, pp. 1563-1568

Yang K.H., Lee M.L., 1991, Analysis of an inverter-driven air-conditioning system and its application in a hot and humid area, International Journal of Energy Research, Vol. 15, Issue 5, pp. 357-365

Wang F., Yoshida H., Masuhara S., Kitagawa H., and Goto K., 2005, Simulation-based automated commissioning method for air-Conditioning systems and its application case study, Proceedings of the 9th International Building Performance Simulation Association Conference, Building Simulation 2005, Montreal, Canada, pp. 1307-1314,

Wang F., Yoshida H., Matsumoto K., 2006, Energy Consumption Estimation for Room Air-conditioners Using Room Temperature Simulation with One-Minute Intervals, International Conference of Enhanced Building Operation, China, Vol.4-3-5

NOMENCLATURE

DI – Discomfort index
E – Energy consumption, (kWh)
N – Total running time, (min)
Q – Cooling/heating production, (kW)
r – Compensation coefficient, (-)
t – Time step
T – Temperature, (°C)
W – Humidity ratio, (-)
Subscriptions
a – Air-conditioner
i – Indoor air
m – Measurement
o – Outdoor air
s – Set point