ROBUST VENTILATION CONTROL FOR BUILDING HVAC PERFORMANCE OPTIMIZATION

Shengwei Wang and Xinhua Xu

Department of Building Services Engineering
The Hong Kong Polytechnic University, Kowloon, Hong Kong
Phone: (852) 2766585, Fax: 27746146, Email: beswwang@polyu.edu.hk

Abstract: Optimal building ventilation control is achieved combining demand controlled ventilation (DCV) and economizer control. The control instability during the transition processes between different control modes is among the major difficulties faced when combining DCV control with economizer control in applications. A robust control strategy, using "freezing", gain scheduling, I-term reset and feedback transition control for different transition processes, is developed addressing the instability problems. The significant energy benefit of using economizer control can be achieved as indicated by over one year's comparison tests on two air-handling units (AHUs) in a building.

Keywords: Demand controlled ventilation, optimal control, air handling unit, economizer, performance optimisation

1. INTRODUCTION

Conventional AHU control employing economizer control introduces a certain fixed fresh air rate to maintain acceptable indoor air quality in the heating mode as well as in the hot seasons [Park et al 1984]. In fact, using the fixed or design ventilation flow rate in control may result in over-ventilation or insufficient ventilation when the occupancy ratio changes. Consequently, it leads to energy waste and/or unsatisfied indoor air quality. Demand controlled ventilation (DCV) is therefore introduced. Various studies and applications about DCV have been reported [Haghighat and Donnini 1992, Wang et al 1999]. Evidently, there are extra control difficulties due to two extra transient processes of the (PID) feedback controls as the results of feedback control applied to the fresh air damper control, which lead to instability phenomena, in the transient region between DCV plus heating mode and total free cooling mode as well as in the transition process from partial free cooling mode to DCV control plus total mechanical cooling mode. In fact, in the conventional AHU control adopting economizer control, control difficulties exist also in transient regions between different modes, as well as in tuning the control loop of multiple processes [Seem 1999].

In the subtropical climate of Hong Kong, the significant energy benefit of using DCV in summer period is obvious because of hot and humid fresh air and obvious changes of indoor occupancy load. However, in Hong Kong, engineers have traditionally believed that the use of economizer was not useful and free cooling provisions are rarely adopted in air-conditioning systems although, in the study of Lam and Hui [Lam and Hui 1995], it was estimated that the economizer could be operated for about 28.3% of a year. In-situ evaluation is required to verify and prove the energy benefits in practical applications.

In this study a robust control strategy, which combines DCV and economizer control, was developed to overcome the control difficulties when DCV control is combined with economizer control [Wang and Xu 2002]. The control strategies were evaluated by implementing them in the digital controllers of an AHU in a building, which were simulated using dynamic models [Wang 1998]. Tests with two different ventilation control strategies (i.e. fresh air damper at fixed position and DCV+ economizer) are conducted in four different weather conditions in Hong Kong. The overall energy, comfort and environmental performance data using these strategies under different load conditions are presented to illustrate the energy performance and robustness of the control strategies developed. The economizer control was also practically utilized in one AHU in a commercial building. The energy and environmental performance of the economizer control was evaluated compared with that of an identical AHU using constant fresh airflow. Both AHUs were monitored on site for over one year simultaneously.

2. AHU AND DCV STRATEGY

Figure 1 shows a schematic diagram of the AHU and the control instrumentations. The AHU control employs two controllers including four PID control loops. The temperature and fresh air flow controller generates the control signals for manipulating the heating coil valve, cooling coil valve and the fresh air damper to control the supply air temperature and fresh air flow rate at their set-points. The DCV based fresh air flow set point reset controller generates fresh air flow set point (demanded minimum fresh air flow rate) for the first controller to maintain acceptable indoor air quality when DCV is beneficial. A dynamic algorithm is used to detect the number of occupants in the indoor space, which considers both the CO_2 concentration and its change rate. The ASHRAE standard, 62-1999 [ASHRAE 1999], requires that the minimum ventilation rate of fresh air for office spaces shall be controlled according to the actual number of occupants in the indoor spaces. On the basis of the CO_2 balance, a dynamic detection method [Wang et al 1999] is utilized to detect the actual number of occupants in this study.

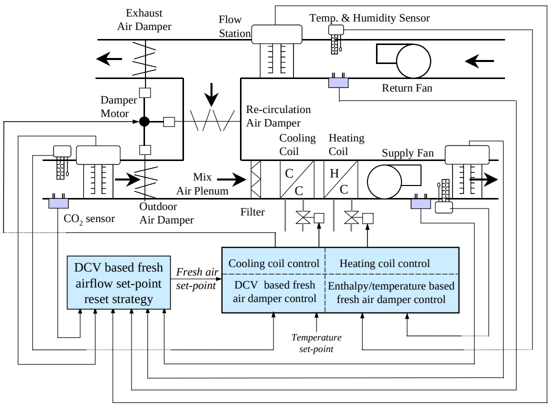

Fig 1. Schematics of an air-handling unit and its control

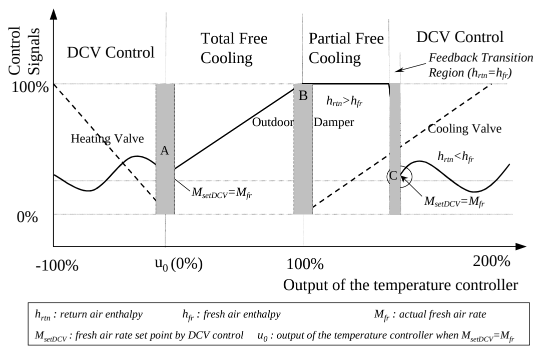

Fig 2. The new split-range sequencing control strategy combining economizer and DCV

3. STRATEGY COMBINING DCV AND ECONOMIZER

3.1 Outline of Strategy Combining DCV and Economizer

In conventional split-range sequencing control strategy, a fixed minimum fresh air is introduced or the fresh air damper keeps at its minimum position when the system is in heating mode or the fresh air enthalpy is larger than that of the return air. In reality, it often results in over-ventilation and insufficient ventilation. Consequently, the control leads to energy waste or/and unsatisfied indoor air quality. DCV is a preferable method for achieving acceptable indoor air quality with minimum energy consumption in the aforesaid conditions. Figure 2 illustrates a new split-range sequencing control strategy developed for AHU control, which combines the AHU temperature control (with economizer control) and the DCV based fresh airflow control. In this control strategy, there are four PID loops. Three loops compose the temperature control corresponding to the control of heating coil, cooling coil and fresh air damper (in free cooling modes). The other composes the fresh air damper control in DCV modes.

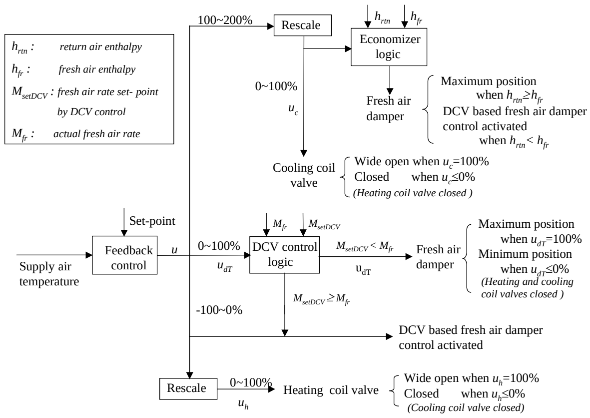

Fig 3. Logic of the new split-range sequencing control strategy combining economizer and DCV

Figure 3 presents detailed description on the relationship between the feedback temperature control output u and the control signals u_c, u_h, and u_{dT} (for the cooling coil valve, the heating coil valve, and the fresh air damper respectively), and the relationship between the temperature control loop and the DCV based fresh air damper control loop. The temperature control output scale ranges from –100% to 200% (generated by three PID functions). The output of the DCV based fresh air damper control is between 0% and 100%. When the output for the temperature control loop is between 100% and 200%, it will be rescaled to 0% to 100% to actuate the cooling coil valve. In the meantime, according to the return air enthalpy and the fresh air enthalpy, economizer logic is utilized to determine whether the DCV based fresh air damper control is activated. When the output from the temperature control loop is between 0% and 100%, the fresh air damper is adjusted to control the fresh air flow rate to maintain the supply air temperature at the set-point, i.e., total free cooling is activated. In this process, the DCV control logic performs checking if the fresh airflow based on temperature controller is sufficient. When the output from the temperature control loop is between 0% and -100%, it is scaled to 0% to 100% to modulate the heating coil valve and the system is in heating mode. In this process, the DCV based fresh air control is activated. When DCV control is combined with economizer control, it is affirmative that operating difficulties will occur between DCV mode and total free cooling mode, between total free cooling mode and partial free cooling mode, and between partial free cooling mode and DCV mode (corresponding to the zone A, B and C shown in figure 2). To overcome these control instability problems, a robust control strategy including three robust schemes at the three different transient regions respectively is developed.

i. *Robust transition control scheme with I-term reset & gain scheduling in the transient region between DCV mode and total free cooling mode;*
ii. *"Freezing" transition control scheme with gain scheduling in the transition process between total free cooling mode and partial free cooling mode;*
iii. *Feedback transition control scheme with I-term reset in the transition from partial free cooling mode to DCV mode.*

The AHU temperature controller utilizes three PIDs to generate control signals for modulating the cooling/heating coil valves and fresh air damper, according the formula $u=PID_{DT}+PID_C-PID_H$. Where, PID_H, PID_C and PID_{DT}, are the PID outputs for heating coil control, the cooling coil control and the fresh air damper control based on temperature control respectively. u is the synthetic output. If the "natural" transition is implemented directly in the transition processes (i.e., the synthetic output is summated directly from the outputs of the three PIDs working independently), alternation and oscillation occur due to the interaction of the three PIDs.

3.2 Robust transition control scheme with I-term reset & gain scheduling in the transient region between DCV mode and total free cooling mode

In heating mode, the PID function (PID_H) for heating coil control is activated, while the PID functions for cooling coil control (PID_C) and temperature-based fresh air damper control (PID_{DT}), together with their I-terms, are frozen at zero. The DCV-based fresh air damper control (PID_{DCV}) is also activated, which controls the fresh air flow rate at its set-point (demanded minimum flow) by comparing the actual fresh air rate with the set-point to produce the PID output. This PID output is used to generate control signal, u_{dDCV}, to control the fresh air damper to maintain acceptable indoor air quality according to the AHRAE ventilation standard [ASHRAE 1999]. As the outdoor air temperature increases, the heating demand decreases till zero and the cooling is required. As the outdoor air temperature in this point is still low, the cooling can be provided by increasing the fresh airflow rate into the building. At this moment, the system enters the total free cooling mode, while the AHU supply air temperature can be controlled by modulating the fresh air damper only. At this point, the PID function of the heating coil control, together with its I-term is frozen at zero. The PID of the DCV based fresh air damper control is frozen also. At the same time, the PID function of the fresh air damper control based on temperature control is activated. To overcome the stability problem of random initial I-term, the I-term of PID_{DT} is set initially equal to the previous I-term of PID_{DCV} (i.e., transition control scheme with I-term reset), smooth transition from DCV control to economizer control can be accomplished or at least oscillation is significantly reduced. To further improve the control stability, gain scheduling is introduced into the transition control (i.e. robust transition control scheme with I-term reset & gain scheduling) allowing the control parameters suitable to the system in the transient region near the crossover point A (see Fig. 2).

3.3 "Freezing" transition control scheme with gain scheduling in the transition process between total free cooling mode and partial free cooling mode

When outdoor air temperature increases further in total free cooling mode, the cooling load increases and PID_{DT} reaches 100%, the mechanical cooling is required. At the moment, PID_{DT}, together with its I-term is frozen at 100%. PID_C, together with its I-term (zero initially) is released and activated. The system enters the partial free cooling mode. Although the "freezing" transition control scheme stabilizes the transition significantly, poor control performance characterized with alternation and oscillation may still occur because overshooting phenomena is liable to occur in the transient region, due to the process nonlinearity and actuator/valve characteristics near upper and lower limits. Therefore, gain scheduling is introduced to the "freezing" transition control scheme allowing the control parameters suitable to the process in the transient region near the crossover point B.

3.4 Feedback transition control scheme with I-term reset in the transition from partial free cooling mode to DCV mode

To ensure the smooth handle over between partial free cooling and DCV mode, the damper control signal is reduced in a controlled speed slow enough allowing that the damper and airflow rate can follow the change of the control signal approximately. In the programming of the control scheme, a travel time is specified as a parameter and the control signal is controlled to change at a constant speed from maximum to minimum at this travel time. In practical operation, this parameter should be noticeably larger than the time required for the damper to move from one limit to the other or the time constant (response time) of the airflow responding to the step changes of control signal. When the damper is reduced to a certain position, the actual fresh airflow rate will reach DCV-based airflow control set point (i.e. demanded minimum fresh airflow rate). At this moment, the PID function (PID_{DCV}) of the DCV-based fresh air damper control is activated to take over the role of the fresh air damper control. The initial I-term of PID_{DCV} is set allowing the damper control signal approximately the same as that just before the handle over.

4. TEST RESULT AND ANALYSIS

4.1 Simulation tests on control performance

Various tests were conducted to validate the strategy and schemes at different working conditions using different proportional gains and gain scheduling algorithms. Only a set of test results is selected to illustrate the performance of the strategy as shown in Table 1. When the transition control scheme with I-term reset was employed, the alternation between the different control modes was diminished greatly. The oscillation of the temperature after using the "transient control scheme with I-term reset" presented much lower frequency and smaller amplitude compared with that using the "natural" transition with random starting. The AIAE (average of the integrated absolute error) decreased significantly from 0.552K to 0.050K (see Table 1). Similarly, according to the number of SSR (the number of actuator starts/stops/reversals) and TD (the actuator normalized ravel distance), the improvement on the control performance using the transition control scheme with I-term reset can be confirmed also as shown in Table1. When the system entered the transient region, the adjusted parameters for gain scheduling were utilized resulting in slower changes of PID outputs, thus slowed down reaction speed, and finally reduced or even avoided overshooting. The AIAE after using the gain scheduling was also less, as shown in Table 1. The total SSR and TD of the actuators of the heating coil valve and the fresh air damper were also reduced significantly.

Table 1. Summary of performance data of different schemes in tests over the transient region between DCV mode and total free cooling mode

Control scheme	SSR				TD				AIAE(K)
	Heating valve	Cooling valve	Fresh air damper	Total	Heating valve	Cooling valve	Fresh air damper	Total	
"Natural" transition with random starting	70	0	628	698	22.27	0	84.11	106.38	0.552
Transition control scheme with I-term reset	252	0	416	668	5.5	0	6.66	12.16	0.05
Robust transition control scheme with I-term reset & gain scheduling	258	0	383	641	4.85	0	3.87	8.72	0.039

Table 2. Summary of energy consumption and environment data in different weather conditions

Weather	Winter		Spring		Cloudy Summer		Sunny Summer	
Strategy	Conventional	Optimal	Conventional	Optimal	Conventional	Optimal	Conventional	Optimal
Fan Consum. (KWh)	88.38	88.73	151.31	151.19	210.84	210.71	342.28	341.04
Saving (%)	-	*-0.39*	-	*0.07*	-	*0.06*	-	*0.36*
Cooling coil consum. (MJ)	384.57	44.33	1140.45	1079.82	2816.53	2613.33	3857.09	3542.89
Saving (%)	-	*88.47*	-	*5.32*	-	*7.21*	-	*8.15*
Electricity Use(KWh)	131.11	93.65	278.02	271.17	523.79	501.08	770.84	734.69
Saving (%)	-	*28.57*	-	*2.46*	-	*4.33*	-	*4.69*
Average CO_2 (ppm)	894.00	588.00	716.00	684.00	651.00	696.00	581.00	617.00
Maximum (ppm)	*1050.00*	*658.00*	*840.00*	*809.00*	*721.00*	*777.00*	*645.00*	*690.00*
Average PPD (%)	6.66	6.65	5.50	5.52	5.17	5.17	7.32	7.39
Maximum PPD (%)	*16.40*	*16.40*	*8.35*	*8.39*	*5.91*	*5.85*	*9.36*	*9.44*

Similarly, "freezing" transition control scheme with gain scheduling and feedback transition control scheme with I-term reset were also validated robust in the transition process between total free cooling mode and partial free cooling mode, and in the transition process from partial free cooling mode to DCV mode respectively. The difference of the test results before and after introducing the robust control schemes are at the same order as the results presented above.

4.2 Simulation tests on energy and environmental performances

Tests with two different ventilation control strategies, i.e., conventional control strategy (fresh air damper at fixed position) and control strategy combining DCV and economizer (optimal strategy), are conducted in four different weather conditions in Hong Kong. The overall energy and environment performance data of these tests are presented in Table 2. An overall COP of chilling system was assumed to be 2.5 as a constant to calculate the overall electricity use. In winter case, the saving of the optimal strategy on cooling coil energy consumption was 88.47%, and the indoor air quality was improved greatly as far as the CO_2 concentrations were concerned. In this season, most of the control process was in total free cooling mode and partial free cooling mode. In spring case, the optimal control of fresh airflow was used, there was only 5.32% saving in cooling coil energy consumption because most of the process was in partial free cooling region and DCV control plus total mechanical cooling process occupied a small part of the whole control process. The indoor air quality was improved slightly indicated by both the average and maximum CO_2 concentrations because more fresh air was taken into indoor spaces in free cooling modes. Average PPD and maximum PPD almost kept unchanged. In cloudy summer case, the optimal control contributed almost no saving in fan energy consumption, but 7.21% saving in cooling coil energy consumption and 4.33% saving in overall electricity consumption. The indoor air quality and the thermal comfort were not affected significantly. In sunny summer case, the optimal control contributed 0.36% saving in fan energy consumption, 8.15% saving in cooling coil energy consumption, and 4.69% saving in overall electricity consumption. Average PPD and maximum PPD almost kept unchanged and average and maximum CO_2 concentrations increased a little because it is hot and humid in summer when total mechanical cooling process is used and DCV control is activated to introduce enough just enough outdoor airflow to satisfy the requirements of indoor air quality. When conventional control strategy was applied, average and maximum CO_2 concentrations were a little smaller because over-ventilation existed in the process, which led to energy waste.

4.3 In-situ experiment on energy and environmental performances of economizer control

To investigate the energy and environmental performances of the air economizer control in Hong Kong, which is within the sub-tropical zone, two AHUs (one with enthalpy-based economizer control and the other with fixed minimum fresh air) in an existing building were monitored over one entire year. The selected building is a commercial center comprising three floors, located in a suburban area. The indoor temperature set-point was 22°C. The monitoring exercise of the study utilized the existing Building Management System (BMS) in the building. From April to October, the outdoor air temperature and humidity were high and only the minimum fresh air was taken into AHUs whether economizer control or minimum fresh air control was applied. Therefore, what concerns economizer control is mainly the difference between these two AHUs from November to March.

In the coldest month (January), the outdoor air dry-bulb temperature, monitored by the BMS, ranged generally between 12°C and 19°C in the operating hours (7:30~24:00). The relative humidity was about 70% in the morning and evening, and 64% at noon. It indicates that almost all the control process with economizer control lied in total free cooling mode. In the whole studied period (from November to March), the outdoor air dry-bulb temperature ranged from 11ºC to 28ºC and the wet-bulb temperature from 7ºC to 25ºC. Over 66.25% of the outdoor air dry-bulb temperature and wet-bulb temperature were between 17ºC and 24ºC and between 13ºC and 20ºC respectively. It shows that the use of more outdoor air can reduce the cooling coil energy consumption greatly at most operation time, and improve the indoor air quality.

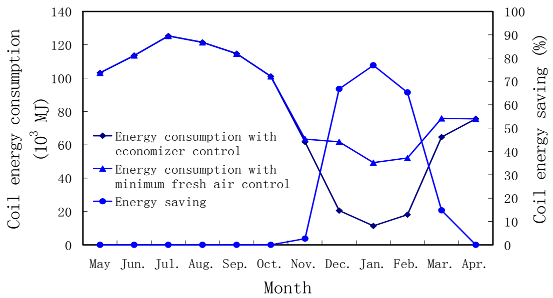

Fig. 4 Monthly coil energy consumptions with economizer control and minimum fresh air control, and coil energy saving

Almost half of the air-conditioned time from November to March was favourable for free cooling to save coil energy consumption. The actual cooling coil energy consumptions were monitored by measuring the variables of both AHUs at airside. Fig. 4 illustrates the percentage of the coil energy consumption saving and the monthly cooling coil energy consumptions of the two AHUs in the entire year using two different control strategies respectively. In the weather condition from November to March, the free cooling mode can be utilized, i.e., economizer control was activated. The coil energy consumption with economizer control was reduced significantly. Compared with the case with minimum fresh air control, the monthly coil energy consumption from November to March was reduced by 3%, 67%, 77%, 65%, and 15% respectively. The total coil energy consumption was reduced by 41.7% in this period. It was found that the most significant reduction on coil energy consumption was in January, which was the coldest month in the year. Based on the total coil energy consumptions of the studied AHUs in the year, the saving on the coil energy consumption with economizer control was estimated to be equivalent approximately to 12.1% of the annual coil energy consumption.

It is usually acceptable to use CO_2 concentration as an IAQ indicator. The relative humidity problem is of concern when free cooling is used. As CO_2

concentration, indoor dry-bulb and wet-bulb temperature were monitored by the BMS over the year, the indoor environmental performance was assessed by analyzing the data of CO_2 concentration in the indoor space and projection of indoor dry-bulb and wet-bulb temperature onto the winter comfort zone. Under partial free cooling modes, the outdoor air flow rate was set to maximum and more fresh air was drawn in to dilute the indoor pollutants. The mean and maximum of CO_2 concentration in this case was found about 60ppm - 150ppm lower than that recorded at the minimum fresh air mode. In total free cooling mode, the CO_2 concentration was about 50ppm - 90ppm lower than that at the minimum fresh air mode. It was concluded that the overall indoor air quality was improved significantly when the economizer was used, since more outdoor air was drawn into the indoor space.

The measurements of indoor dry-bulb and wet-bulb temperature in the studied period were superimposed onto the winter comfort zone (assumed clothing: 0.9 clo). In the period of partial free cooling and total free cooling, 89.1% and 78.2% of the measurements were found within the comfort zone respectively. About 9.4% and 20.4% fell to the left of the comfort zone (close to the zone) at partial free cooling mode and total free cooling mode respectively, while it is colder than that preferred. Less than 2% of measurements at both free cooling modes fell in other regions. It indicates that the use of free cooling did not cause humidity problem.

During the rest period of the five months, 82.5% of measurement data were observed within the comfort zone when fresh air was controlled at minimum flow rate. About 10.4% of measurements was allocated above the line of 18ºC wet-bulb temperature, while relatively humid was higher than preferred value. The other 6.4% of measurement data fell to the left of the comfort zone, while the temperature was colder than preferred. The humidity problem in minimum fresh air mode was due to the low cooling load and high outdoor air humidity that resulted in that the mechanical cooling did not provide sufficient dehumidification. The overcooling of space in the free cooling modes was noticeably more significant than that at minimum outdoor air flow mode, although it was not serious. In principle, the use of economizer control should not make the situation worse since the free air flow should be set to minimum if the outdoor air is too low. The measurements show that the system control might need to be improved by tuning the temperature control in free cooling modes. To eliminate overcooling at very cold period, heating should be added in the system.

5. CONCLUSION

The transition control scheme with I-term reset diminishes the alternation and oscillation in the transient region between total free cooling mode and DCV mode. The use of gain scheduling (i.e. the robust transition control scheme with I-term reset & gain scheduling) further reduces the possibility of alternation and oscillation in the transient region. "Freezing" transition control scheme with gain scheduling in the transition process between total free cooling mode and partial free cooling mode can significantly increase the control stability. The feedback transition control scheme with I-term reset achieves better control stability in the transition process from partial free cooling mode to DCV control by avoiding the instable control during the initial stage of the DCV based fresh air damper control. The optimal robust control strategy combining DCV and economizer can achieve significant energy saving and improve indoor air quality in winter season even in Hong Kong. In spring season, the indoor air quality can be improved significantly while noticeable energy saving can be achieved. In summer season, significant energy saving can be achieved by DCV and the indoor air quality can be maintained acceptable.

ACKNOWLEDGEMENT

The work presented is financially supported by a grant from the Research Grants Council of the Hong Kong SAR and a research grant of The Hong Kong Polytechnic University.

REFERENCE

ASHRAE. 1999. ASHRAE Standard 62-1999. *Ventilation for acceptable indoor quality*, Atlanta.

Haghighat F, Donnini G. 1992. IAQ and energy management by demand controlled ventilation. *Environment Technology*, 1992, 13: 351-359..

Lam, C. and Hui, C.M. 1995. Outdoor Design Conditions for HVAC System Design and Energy Estimation for Buildings in Hong Kong. *Energy and Buildings*, 1995, 22: 25 – 43.

Park. C., Kelly. G. F., and Kao. J. Y. 1984. Economizer Algorithms for Energy Management and Control System. Nat. Bur. (US) NBSIR 84-2832.

Seem, J.E. Jan. 1999. A new sequencing control strategy for air-handling units. *HVAC&R Research*, Vol. 5, No. 1.

Wang SW. 1998. Dynamic simulation of a building central chilling system and evaluation of EMCS on-line control strategies. Building and Environment, V33(1), 1-20.

Wang, S.W.; John Burnnet; Chong Hoishing. 1999. Experimental validation of CO_2 based occupancy detection demanded-controlled ventilation. *Indoor Built Environment*, 1999,8: 377-391.

Wang SW and Xu XH. 2002. A robust control strategy for combining DCV control with economizer control. *Energy Conversion and Management* Vol.43 pp:2569-2588.