World Academy of Science, Engineering and Technology
International Journal of Energy and Environmental Engineering
Vol:9, No:7, 2015

Development of Sustainable Building Environmental Model (SBEM) in Hong Kong

Kwok W. Mui, Ling T. Wong, F. Xiao, Chin T. Cheung, Ho C. Yu

Open Science Index, Energy and Environmental Engineering Vol:9, No:7, 2015 publications.waset.org/10001743/pdf

***Abstract*—**This study addresses a concept of the Sustainable Building Environmental Model (SBEM) developed to optimize energy consumption in air conditioning and ventilation (ACV) systems without any deterioration of indoor environmental quality (IEQ). The SBEM incorporates two main components: an adaptive comfort temperature control module (ACT) and a new carbon dioxide demand control module (nDCV). These two modules take an innovative approach to maintain satisfaction of the Indoor Environmental Quality (IEQ) with optimum energy consumption; they provide a rational basis of effective control. A total of 2133 sets of measurement data of indoor air temperature (T_a), relative humidity (R_h) and carbon dioxide concentration (CO_2) were conducted in some Hong Kong offices to investigate the potential of integrating the SBEM.

A simulation was used to evaluate the dynamic performance of the energy and air conditioning system with the integration of the SBEM in an air-conditioned building. It allows us make a clear picture of the control strategies and performed any pre-tuned of controllers before utilized in real systems. With the integration of SBEM, it was able to save up to 12.3% in simulation of overall electricity consumption, and maintain the average carbon dioxide concentration within 1000ppm and occupant dissatisfaction in 20%.

***Keywords*—**Sustainable building environmental model (SBEM), adaptive comfort temperature (ACT), new demand control ventilation (nDCV), energy saving.

I. Introduction

AIR conditioning consumed about half of the total electricity usage in air-conditioned buildings; a policy of energy conservation in air conditioning system should be applied to enhance the energy efficiency in building of Hong Kong. In this study, a concept of the Sustainable Building Environmental Model (SBEM) is developed to optimize energy consumption in ACV systems without any deterioration of indoor environmental quality (IEQ), however, this model has not been applied in many buildings. Documentation references and technical support for practitioners are urgently required for upgrading the air-conditioning systems to shoot for sustainable use of energy. For the SEBM, it is sub-divided into two modules: Adaptive Comfort Temperature (ACT) module and new Demand Control Ventilation (nDCV) module. It aims to enhance and promote the conventional operation of the air-conditioning systems by document references with technical supports. Temperature reset with adaptive comfort temperature control and the new demand control fresh air ventilation system of air-conditioned buildings in Hong Kong will be detailed (Fig. 1). In order to investigate the potential of integrating the SBEM in air-conditioned buildings a survey of 2133 Hong Kong office buildings was carried out to gather valuable information on the existing air-conditioned system design values in different grades of private commercial buildings in Hong Kong.

K. W. Mui is with The Hong Kong Polytechnic University, HKSAR, China (phone: 852-27665835; fax: 27657198; e-mail: behorace@polyu.edu.hk).

L. T. Wong, F. Xiao, C. T. Cheung, and H. C. Yu are with The Hong Kong Polytechnic University, HKSAR, China (e-mail: ling-tim.wong@polyu.edu.hk, befx@connect.polyu.hk, be.toby@connect.polyu.hk, yu.ho.ching@connect.polyu.hk).

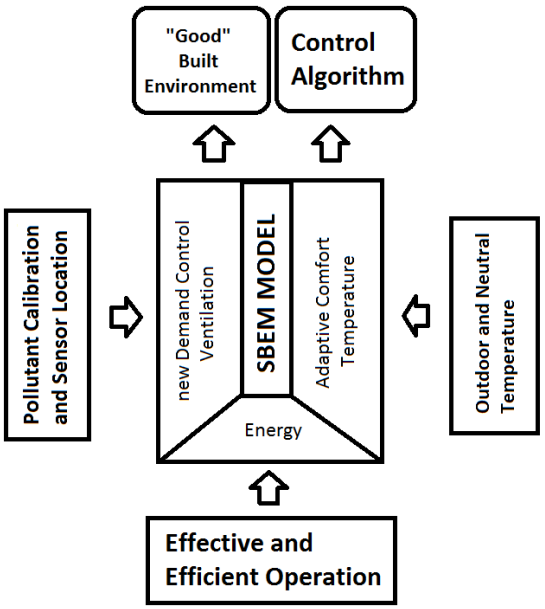


Fig. 1 Conceptual diagram for the sustainable building environmental model (SBEM)

II. Adaptive Comfort Temperature (ACT) Module

One of the main problems with thermal comfort in air-conditioned buildings in Hong Kong is that of being too cold, rather than being too warm or stuffy. Adaptive Comfort Temperature (ACT) is defined as the indoor air temperature at which a target percentage of satisfaction with thermal comfort is attained. It is a function of immediate outdoor temperature. The contemporary practice is to control the room temperature at a fixed set point. Existing fixed supply air set point in air-conditioning system is not appropriated. The ACT control model is a linear regression model that relates indoor design temperatures or an acceptable temperature range, to outdoor meteorological or climatological parameters. In this study, the regressed linear ACT equation in Hong Kong is established.

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The ACT model is a module in the SEBM for optimising energy effective IEQ control. It can reduce the temperature shock and reduce the dissatisfaction rate of occupants [1].

$$T_n = 18.303 + 0.158 \times T_o \quad (1)$$

This linear relationship between the outdoor air temperature and the indoor comfort temperature was further capped at both the high and low temperature limits based on maximum allowed percentage of occupant dissatisfaction. With the usual limit 20% PPD of which is taken as an indicator for sick building syndrome. Taking this approach, the upper cap and lower cap is at 24.8°C and 19.2°C respectively, as the unacceptability vote is 20% in both situations [1].

III. New Demand Control Ventilation (nDCV) Module

From the existing standard of ventilation, acceptable IAQ calls for substantial increases in fresh air ventilation rates by as much as 300 percent above that specified in standard 62 [2]. This also means a dramatic increase in energy costs for buildings in localities with hot and humid summers, and/or cold and dry winters. Thus, the strategy of supplying a large quantity of fresh air, regardless of fluctuation in the building occupancy results energy wastage. However, many new buildings are not picked new design concepts and some engineers translate the level of occupant satisfaction to the fresh air change rate when making design decisions. Metabolic carbon dioxide (CO_2) concentration can be used as a surrogate indicator of air quality. A Demand Controlled Ventilation (DCV) system offers a solution by modulating outdoor air quantities according to the space CO_2 concentration.

In typical, misconception of conventional DCV systems conserved energy presumes scarified occupant thermal comfort by systems of only temperature control. It only takes into account of indoor carbon dioxide concentration to regulate the outdoor air damper to control the outdoor air flow rate. Pollutant calibration of the office where the minimum turn down ratio of the outdoor air quantity is capped by health criteria and the nDCV module is therefore established [3]. It can save energy for conditioning fresh air without any deterioration of IAQ.

Different buildings have their own pollutant characteristics. A comprehensive IAQ control would require the system calibration to be done for expected pollutant levels. This has reported in a finished longitudinal monitoring study that representative major pollutants in Hong Kong buildings for IAQ are radon, total volatile organic compounds, formaldehyde and carbon monoxide. Among the pollutants monitored, only radon was found to exceed the IAQ certification scheme of 200Bq/m^3, if the outdoor air system is turned off [4]. Therefore, radon gas was chosen as a calibrator because of the abundance of residue radon embedded in the concrete used in the high-rise buildings in Hong Kong.

As source control and adequate supply of outdoor air are two strategies that are used to achieve good IAQ. Research team established a procedure of calibrating the building in respect of managing the IAQ. The objective is to set the minimum fresh air quantity which is a function of the indoor pollutant concentrations such as radon (source) and metabolic CO_2 (adequate supply of outdoor air) respectively [3], [5].

The procedure steps are as follows:

- Determine the effective air volume of an office.
- Record the conditions of temperature and humidity, the method of air distribution (e.g. ceiling, sidewall and floor outlets) and the hours of system operation.
- Collect the specifications for the air-side system (e.g. type, control method, supply air capacity, fresh air and return air flow rates, etc.), and the accessory details (e.g. types of diffuser and fresh air damper).
- Measure the air flow rates (e.g. fresh air, supply air, return air, etc.) and other physical data for the air-side system (e.g. supply air, return air and mixed air temperatures).
- Establish a method to determine the fresh air damper characteristics; and using the relationship of the opening percentage of fresh air damper, the fresh air supply flow rate and the target pollutant concentrations (e.g. radon and CO_2), the experiment of determining the minimum flow rate can be performed.

IV. Energy Consumption

To calculate the energy consumption resulted from the integration of the SBEM, the survey result and the new weather data, the following equation is used with the assumptions of no fan heat gain for the HVAC system and a 95% saturation in leaving coil condition [6].

$$Q = \rho \times V \times \left[C_{pa} \times (T_{on} - T_{le}) + h_{fg} \times (g_{on} - g_{le})\right] \times S \quad (2)$$

Relative humidity to moisture content is calculated by (3):

$$g = 0.622 \times \frac{\phi \times P_{SS}}{P_{at} - \phi \times P_{SS}} \quad (3)$$

Wet bulb to moisture content is calculated by (4):

$$g = \frac{0.622}{\left[\frac{P_{at}}{P_{SS'} - P_{at} \times A \times (t - t')} - 1\right]} \quad (4)$$

Saturated vapour pressure is given by (5):

$$P_{SS} = \log^{-1}\left[\begin{array}{l} 30.59051 - 8.2 \times \log(t + 273.16) + 0.0024804 \\ \times (t + 273.16) - \dfrac{3142.31}{(t + 273.16)} \end{array}\right] \quad (5)$$

where

Q = Energy consumption, kJ
ρ = Density of air = 1.2kgm^{-3}
V = Total air volume handled, m^3/s
c_{pa} = Specific heat capacity of air = 1.023kJkg^{-1}K^{-1}
T_{on} = On coil temperature, °C
T_{le} = Leaving coil temperature, °C
h_{fg} = Latent heat of evaporation of water = 2454kJkg^{-1}
g_{on} = On coil moisture content, kgkg^{-1}

g_{le} = Leaving coil moisture content, $kgkg^{-1}$
g = Moisture content, $kgkg^{-1}$
P_{ss} = Saturated vapour pressure at the same temp., kPa
P_{at} = Atmospheric pressure = 101.325kPa
$P_{ss'}$ = Saturated vapour pressure at wet bulb temp., kPa
A = A constant = 6.66×10^{-4} °C^{-1}
ϕ = Relative humidity
t = Dry bulb temperature, °C
t' = Wet bulb temperature, °C
S = Time, seconds

V. Results and Discussion

A. Building Survey

Based on the definitions described in the Technical Notes of Hong Kong Property Review, office buildings are graded as follows [7].

TABLE I
Characteristics of Different Grades of Office in Hong Kong

Building grade	A	B	C
Characteristics	• Modern with high-quality finishes; flexible layout; large floor plates; spacious, well-decorated lobbies and circulation areas. • Effective central air-conditioning; good lift services zoned for passengers and goods deliveries. • Professional management; parking facilities normally available.	• Ordinary design with good quality finishes; flexible layout; average-sized floor plates. adequate lobbies; • Central or free-standing air-conditioning; adequate lift services. • Good management; parking facilities not essential.	• Plain with basic finishes; less flexible layout; small floor plates; basic lobbies. • Generally without central air-conditioning; barely adequate or inadequate lift services. • Minimal to average management; no parking facilities.

TABLE II
Summary of Survey Data

Building grade	Type of air-side system	Number of offices surveyed	Indoor design values in HK			Actual averages recorded		
			CO_2 (ppm)	Temp (°C)	RH (%)	CO_2 (ppm)	Temp (°C)	RH (%)
A	CAV	229	800	23	50	570	23.2	62
	FCU	56	800	23	50	718	22.9	62
	VAV	1007	800	23	50	743	23.0	57
	VRV	49	800	23	50	603	23.1	63
B	CAV	52	800	24	55	583	22.4	67
	FCU	334	800	24	55	674	22.7	65
	ST	7	800	24	55	683	22.9	66
	VAV	36	800	24	55	573	23.2	64
	VRV	37	800	24	55	589	23.1	65
C	CAV	28	800	25.5	60	568	22.2	66
	FCU	206	800	25.5	60	626	22.6	63
	ST	92	800	25.5	60	634	23.2	62

Physical data on indoor air temperature (T_a), relative humidity (R_h) and carbon dioxide concentration (CO_2) were conducted and reviewed in some Grade A, B, and C offices, respectively in 9, 14 and 20 districts, including 1341, 466 and 326 set of data samples. All surveyed offices were assigned with certificate which satisfying the minimum requirements of Hong Kong indoor air quality objectives (HKEPD 2003). The type of ventilation system, i.e. variable air volume (VAV), variable refrigerant volume (VRV), constant air volume (CAV), fan coil unit (FCU) and split type (ST) air conditioner, was recognized in all offices. The database was developed to update current indoor design parameters and conditions of air-conditioned offices in Hong Kong. A summary of the survey is illustrated in Table II.

Several differences have been identified via the surveyed parameters between this study and our previous office database conducted 10 years ago [6]. Insignificant difference of T_a (average: 22.9°C; standard deviation: 1.3°C), R_h (60.6; 8.7%) and CO_2 (682; 194ppm) was reported among the surveyed offices, except a lower R_h (58.5; 8.8%) being recorded in Grade A offices (T_a: 23.1°C; R_h: 58.5%; CO_2: 708ppm). It shows an enhancement on thermal environment and air quality in Grade B&C offices (T_a: 22.7°C; R_h: 65.3%; CO_2: 650ppm & T_a: 22.8°C; R_h: 63%; CO_2: 623ppm) as compared with Grade A nowadays. Despite a smaller stock being observed in Grade B&C offices (37% of total stock in year 2013), a remarkable cooling energy saving potential is still expected which energy control strategies shall not be ignored in these areas. Besides, up to 30% of the Grade C offices were found ventilated by split type air-conditioners installed together with additional exhaust fans. Notwithstanding a low CO_2 concentration was maintained by sparse occupancy, it was not energy efficient design especially for offices which accommodating more staffs. Implementation of SBEM is therefore a significant step to improve ventilation system efficiency and to maintain occupants' thermal and IAQ satisfactory in all Grade A, B, C offices in Hong Kong.

B. Evaluation of SBEM System

The building investigated is a 43-storey office building with a two-storey basement. The air conditioning system is VAV system serving various sections of a floor, regulating the supply airflow to a group of supply air diffusers in response to thermal load in the region served by the diffusers. The volume of the occupied zone is 3265m^3, and the volume of the roof void above the ceiling (the upper zone) is 1071m^3. For the AHUs (4 numbers) with the integration of adaptive comfort temperature module, the chilled water flow rate of the cooling coil is modulated to control the space temperature according to the outdoor air temperature. For the new demand control ventilation model, the fresh airflow rate is changed according to the indoor carbon dioxide concentration with the minimum fresh air supply flow rate.

Two simulations were conducted to test the dynamic performance of the conventional air-conditioning and the system with the integration of SBEM. Table III shows the simulation results for two scenarios.

After the dynamic simulation of the existing system and the system with SBEM, an installation of the SBEM in a mock up office was performed to validate and compare the results between the simulations. For the new demand control ventilation strategies, the number of occupancy was recorded

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and the fresh airflow was changed with the carbon dioxide concentration at return air plenum with minimum fresh air supply quantity. With the use of the simulation, the difference of the fresh airflow rate in two ventilating system was 10%. Comparing with the measured carbon dioxide concentration at the return air plenum of the conventional fresh air system and with the integration of SBEM in field measurement as shown in Fig. 1, saving was found in the measured result (14%). Small differences were found between the simulated and real situations, the new demand control ventilation strategy was validated and the new demand control ventilation can control the pollutant level and carbon dioxide within the allowed level.

TABLE III
SUMMARY OF ENERGY AND ENVIRONMENT TEST DATA

Strategy	Conventional	ACT Model	new DCV-based Fresh Air Flow	Overall Control Optimization
Fan Consumption (MJ)	1069.38	1037.28	1055.35	1006.52
Savings (%)	-	***2.99***	***1.30***	***5.87***
Coil Consumption (MJ)	3474.49	3428.23	2894.36	2877.87
Savings (%)	-	***1.33***	***16.70***	***17.17***
Overall Electricity Consumption (MJ)	2459.08	2408.57	2213.09	2157.67
Savings (%)	-	***2.05***	***10.00***	***12.26***

VI. CONCLUSION

The improper implementation of certain conventional control techniques, particularly the adaptive comfort temperature (ACT) control and demand control ventilation (DCV), leads to unsatisfactory IEQ performance. And so does emphasis on energy saving only. The evolution of a more proficient design and operation protocol for the building services systems resulted in the Building Environmental Performance Model (BEPM) being developed for use in Hong Kong.

From a comprehensive survey on the designs and measured values of the commonly used air conditioning systems in Hong Kong, it was found that the total air conditioning energy consumption could be saved for office buildings if the SBEM was applied. With the integration of the SBEM in the VAV system, the saving of energy can be achieved by adaptive comfort temperature model and new demand control ventilation model. The SBEM was found to be very successful. It was able to save up to about 12% of energy used, and maintain the occupant dissatisfaction at around 20%, which is taken as the criteria for acceptability.

ACKNOWLEDGMENT

The work described in this paper was substantially/partially supported by Internal Competitive Research Grant (CRG: G-YL19), The Hong Kong Polytechnic University, Hong Kong Special Administrative Region, China, and The Environment and Conservation Fund (ECF: K-ZJJV), The Government of the Hong Kong Special Administrative Region, China.

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