Development of a dual-mode demand control ventilation strategy for indoor air quality control and energy saving

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Abstract

A dual-mode demand control ventilation strategy was established targeting at use in buildings where the number of occupants varies frequently. The first contaminant chosen for sensor control is CO_2 and the second is a non-occupant-related indoor pollutant which indicates the demand of fresh air to dilute the non-occupant-related indoor contaminants. Experiments were conducted to verify the performance of this control strategy. The experimental results showed that an acceptable indoor air quality could be obtained. More than 90% of the occupants thought that the indoor air quality was acceptable. Comparing with the original fixed-rate ventilation control strategy, about 8.3–28.3% of the daily electrical energy could be saved.

Keywords: Indoor air quality; Demand control ventilation; Carbon dioxide; Radon; Purging

1. Introduction

Ventilation is one method to maintain good indoor air quality. The more fresh air is brought into the indoor environment, the better the indoor air quality can be achieved if the fresh air comes from non-polluted ambient source. However, conditioning fresh air can consume a lot of energy, especially in Asian cities where humidity is high in summer. It has been noticed that 30% or more of the annual heating and cooling cost is spent in handling the fresh air in a typical office building [1,2]. Over-ventilation may lead to a significant waste of energy. Therefore, an operationally cost-effective ventilation control system is very important in buildings. Ventilation control strategies such as sensible temperature-based air-side economizer, enthalpy-based air-side economizer and demand control ventilation (DCV) have been demonstrated in many buildings all over the world. The sensible temperature-based air-side economizer uses the outdoor air temperature (dry-bulb temperature) as the control signal to adjust the fresh air supply to the prescribed supply rate. It usually can reduce the annual cooling energy by around 30% in moderate climates such as in Columbia, MO, US [3,4]. The enthalpy-based air-side economizer considers the total heat of the outside, re-circulated and mixed air to determine the fresh air supply rate. It can have a better performance than the sensible temperature-based air-side economizer in terms of energy saving because it traces both the sensible and latent heat of the dry-air and moisture, especially in highly humid climates. However, the enthalpy sensor is much more expensive and it usually needs a semi-annual calibration. While using these two kinds of ventilation control strategy, fresh air is brought in at the prescribed rate and does not directly correspond to the variation in occupancy. So if these two ventilation control strategies are used in institutional or similar buildings where the number of occupants varies frequently, they may not be able to maintain a good indoor air quality and avoid over-ventilation at the same time. Demand control ventilation makes use of some methods to estimate the actual number of occupants and adjusts the fresh air supply rate to meet the demand of fresh air per person. This approach is more suitable for buildings with varying occupancy during the day such as auditoriums, libraries, classrooms and theatres. In recent years, CO_2 concentration has been widely used to measure the occupancy for the demand control ventilation system as it is an excellent surrogate gas for the concentrations of occupant-related contaminants [1,5–7]. By using the dynamic CO_2 detection method, the occupancy can be determined accurately and the change

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Nomenclature

A	Area of the material that emits radon (m^2)
C_i	Indoor radon concentration (Bq m^{-3})
C_{i0}	Indoor radon concentration at the beginning of the purging sequence (Bq m^{-3})
C_o	Outdoor radon concentration (Bq m^{-3})
C_{p2}	Radon level after Purging sequence 2 (Bq m^{-3})
C_{sco2}	CO_2 set point (ppm)
C_{oco2}	Outdoor CO_2 concentration (ppm)
E	Radon emanation rate of building material (Bq (m^{-2} h^{-1}))
Q	Ventilation rate of the premises (m^3 h^{-1})
K_d	Differential parameter of the PID controller
K_i	Integral parameter of the PID controller
K_p	Proportional parameter of the PID controller
N	CO_2 generation rate per person (l min^{-1})
t_{pg}	Purging duration (h)
V	Effective volume of the premise (m^3)
V_o	The outdoor air flow rate per person (l s^{-1})
X	Damper position, which is carried out by the PID controller (%)
$\Delta y(k)$	Difference between the CO_2/radon setpoint and the kth sampled CO_2/radon level
λ	^{222}Radon decay constant (7.553585×10^{-3} h^{-1})

of occupancy can be detected with a fast response time [8]. Based on the actual occupancy, the outdoor air supply rate per person recommended in the industrial standards such as ASHRAE 62-1999 [9] can be met and over-ventilation can be avoided. Rock and Wu's work [1] shows that CO_2 based demand control ventilation could offer better performance on energy saving than fixed-rate and economizer ventilation in hot and humid climate.

In Hong Kong, where such climate is normal from May to September as the average temperature and relative humidity during this period are as high as 27.6°C and 81%, respectively. CO_2 based demand control ventilation may be a good way to provide indoor air quality and energy saving. However, CO_2 is only an indicator for occupant-related indoor pollutant sources. The CO_2 based DCV can only guarantee that the fresh air intake is enough to dilute the occupant-related pollutants. Whether the levels of the non-occupant-related pollutants are acceptable or not is not considered. ASHRAE 62-1999 [9] points out that using CO_2 as the indicator of bio-effluents does not eliminate the need to consider other contaminants, a number of which have received increasing attention in recent years such as radon and VOCs.

Since the end of 1997, in order to study the performance of the CO_2 based demand control ventilation strategy, a series of site measurements had been conducted in a typical lecture theatre at the Hong Kong University of Science and Technology (HKUST). During the experiments, the major indoor pollutants such as CO_2, radon, TVOC, and formaldehyde were measured in detail, among which CO_2 and part of the VOCs are occupant-related and radon, formaldehyde and part of the VOCs are non-occupant-related. The results showed that by using only CO_2 based demand control ventilation, the non-occupant-related indoor pollutants such as radon might not be maintained at acceptable levels under some circumstances. Based on the findings from the experiments, a new dual-mode demand control ventilation strategy, which aims at maintaining some of the occupant-related and non-occupant-related indoor air pollutants at acceptable levels was developed. Experiments were conducted in a medium-sized lecture theatre at HKUST to verify the performance of this new demand control ventilation strategy. During the experimental study, both the indoor air quality and the energy consumption while using the developed dual-mode demand control ventilation strategy were studied.

2. Experimental setup and methods

Both the site measurements on some of the indoor air quality parameters and the verification of the dual-mode demand control ventilation strategy performance were conducted in a lecture theatre at the Hong Kong University of Science and Technology. The lecture theatre is on the ground floor of the northern perimeter of the Academic Building. It has a total floor area of about 150 m^2, a volume of about 500 m^3, and a maximum capacity of 130 occupants. As there is variable occupancy, the venue is very suitable for the study of demand control ventilation. A HVAC system was used to serve only this lecture theatre. It is a single-zone, variable-air-volume (VAV) system. A direct digital controller (DDC) is used in this system to control the chilled water valve and the supply air inlet guide vane actuator to maintain the desired supply air temperature and static pressure. A fresh air damper is

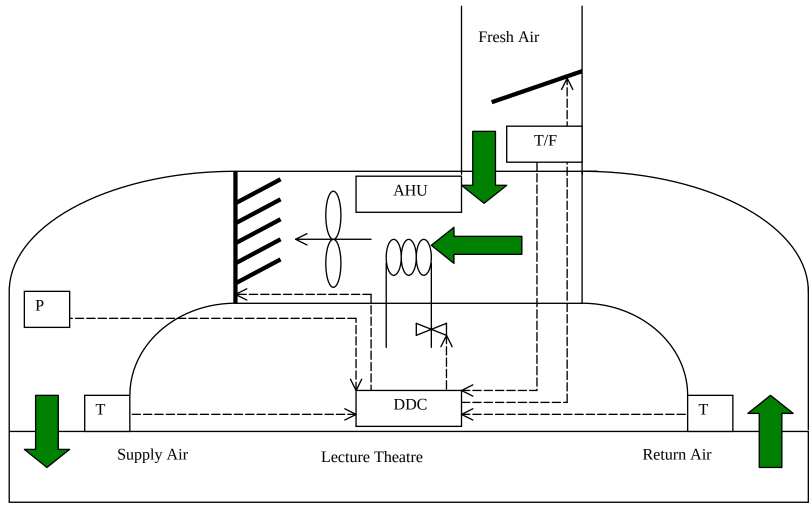

Fig. 1. Schematic diagram of the HVAC system serving the lecture theatre.

used to control the fresh air intake. Its fresh air controller is a fixed-rate ventilation controller, which maintains the fresh air flow rate at 1040 l s^{-1}(8 l s^{-1} per person for 130 persons). Fig. 1 shows the schematic diagram of the HVAC system serving this lecture theatre.

2.1. Site measurement on some of the indoor air quality parameters

The site measurement on some indoor air quality parameter was conducted from December, 1997 to February, 1999. The goal was to study the performance of the traditional CO_2 based demand control ventilation strategy. During the experiments, the original fixed-rate fresh air control system was suspended and a CO_2 based demand control system was used. A fresh air supply rate of 8 l s^{-1} per person was used during the lecture hours as required by the ASHRAE standard 62-1999. Under this demand control ventilation, the major indoor air pollutants were continuously measured in all the experiments.

These experiments covered periods when different fresh air supply rates and different occupancy levels could be encountered. In the site measurement, a solid state radon detector, Niton Rad7, was used in the experiments to measure the radon level. The overall calibration accuracy of the detector is 5% based on a sensitivity of 0.4 counts min^{-1} $pCil^{-1}$. The range of it is 0.1–5000 $pCil^{-1}$. During the measurements, one detector was located at the breathing zone in the lecture theatre and another detector was put into the return air duct. The radon level in the return air duct was continuously measured simultaneously with that in the breathing zone. Besides, an additional Rad7 detector was placed outside the lecture theatre for continuous measurement of the outdoor radon level. During the experiments, the sample rate was set at 30 min^{-1}.

An INNOVA 1312 Photo-acoustic Multi-gas Monitor connected with B& K 1303 Multi-points Sampler and Doser units were used in the experiments to collect the information of CO_2 levels at multiple points within the lecture room. Four CO_2 sampling points were set up during the experiments. One was located in the return air duct, one was located at the fresh air louver outside the lecture theatre and the another two sampling points were placed at the front and the back rows of the lecture theatre at an elevation of about 1 m which is comparable to the breathing zone. In the experiments, the INNOVA 1312 Photo-acoustic Multi-gas Monitor was also used to collect the information of sulfur hexafluoride (SF_6) to measure the ventilation rates that were used in our research to calculate the radon emanation rate of the building materials in the lecture theatre. The ventilation rates were measured using the tracer gas decay technique. In our experiments, sulfur hexafluoride gas was dosed in the lecture theatre as the tracer gas and was well-mixed so that the sulfur hexafluoride concentrations at the front and back rows of the lecture theatre differed no more than 10%. This satisfied the ASTM's requirement that the tracer gas concentration within the building should be uniform within 10% [10,11]. Then, the sulfur hexafluoride gas decayed in the lecture theatre. By measuring its decaying rate, the air change rates could be carried out.

A ppbRAE ppb VOC monitor PGM-7240 Photo-ionization Detector was used to measure the TVOC level. The accuracy of this VOC monitor is 10% of the reading or 20 ppb and its measurement range is 0-9999 ppb. During the site measurement, the ppb RAE VOC monitor was located at the breathing zone near the CO_2 monitor at the front row to measure the TVOC level in the lecture theatre. In order to measure the formaldehyde level in the lecture theatre, a Bionics TG1900KA gas detector, which is based on the principal of membrane electrolysis was used and was put at the breathing zone near the ppbRAE VOC meter. The

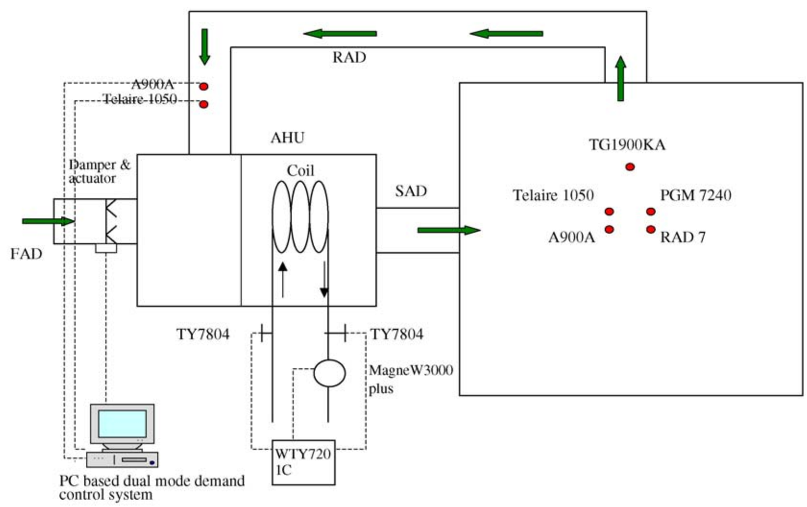

Fig. 2. The schematic diagram of the experimental setup.

range of this formaldehyde detector is 0 to 2 ppm with an accuracy of 0.01 ppm.

2.2. Verification of the performance of the dual-mode demand control ventilation strategy

The experiments to verify the performance of the dual-mode demand control ventilation strategy were conducted from August to October of 2000, which covered the summer vacation and the regular semester period. During the experiments, different occupancy levels were encountered.

A PC based controller was developed to implement the developed demand control ventilation strategy. In the experiments, we used this controller instead of its original fixed-rate ventilation controller for the fresh air control. One Telaire-1050 CO_2 monitor was used to measure the CO_2 level and transmit the signal to the controller. The accuracy of this CO_2 monitor is 5% of the reading if it is less than 50 ppm. Otherwise, it is 50 ppm. The maximum CO_2 level that can be detected by this monitor is 2000 ppm. A Honeywell radon monitor A900A was used to measure the radon level. The measurement range of this radon monitor is from 0.1 to 999 pCi l^{-1} with the accuracy of 25% or 1 pCi l^{-1}, depending on which is greater. With some modifications on the circuit of this controller, it was able to transmit the radon level to the controller. Both the CO_2 and radon monitors were put at the return air duct. A Telaire-1050 CO_2 monitor, one ppbRAE VOC monitor, a TG1900KA formaldehyde monitor and a Rad 7 radon monitor were put at the breathing zone of the lecture theatre to measure the CO_2, Radon, TVOC and formaldehyde. Besides the indoor air quality measurement, a questionnaire survey was also conducted to see if the indoor occupants thought that the indoor air quality was acceptable or not while using dual-mode demand control ventilation. The questionnaires were handed out to the occupants randomly and were collected back after the occupants left the lecture theatre. In the experiments, a total of 500 questionnaires were handed out and 382 questionnaires were collected back.

In order to verify the performance of our dual-mode demand control ventilation on energy consumption, A Yamatake energy metering system was installed into the chilled water pipe to monitor the consumption of cooling energy. This energy metering system is composed of a Yamatake MagneW3000 plus electromagnetic flow meter, a Yamatake WTY7201C energy meter and a well matched pair of high precision platinum resistance sensors, Yamatake TY7804. The overall accuracy of this energy metering system is 2.0%. For the purpose of comparison, the original fixed-rate ventilation control system was run under almost the same occupancy levels and the energy consumption was recorded. As the lecture theatre was used as a classroom, the variation of the occupancy level in the theatre was periodic on a weekly basis. For the comparison of energy consumption, we executed the original fixed-rate ventilation under the same occupancy levels as that while using the developed control strategy. During all experiments, the indoor air temperature was fixed at 22°C and the relative humidity was around 70%. Fig. 2 shows the experimental setup.

3. Experimental results and discussion for the site measurement

In the lecture theatre, lecture hours started generally at 8:00 am to 9:00 am and might continue until 9:30 pm if an evening class was scheduled. The CO_2 based demand control ventilation system ran during all the lecture hours. From our measurements, the daily average indoor CO_2 level during lecture hours was found to range from 508 which occurred when only a few occupants were in the theatre to

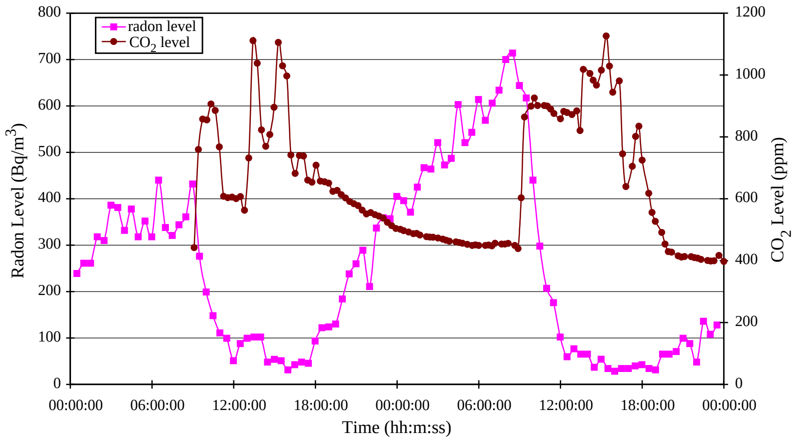

Fig. 3. Typical radon and CO_2 profiles in the lecture theatre while using CO_2 based demand control ventilation.

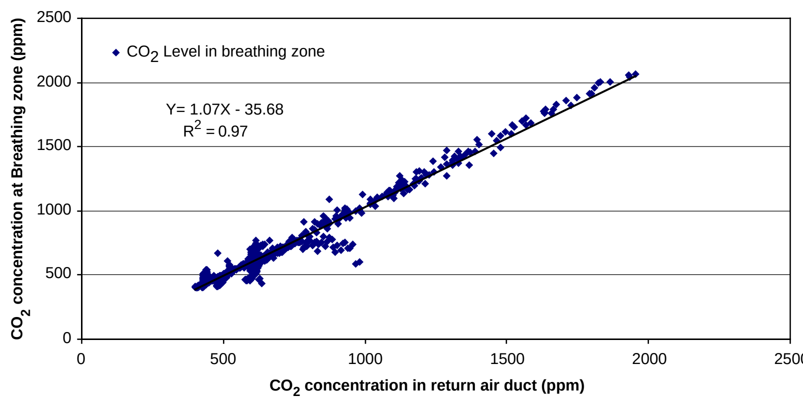

Fig. 4. Correlation between the CO_2 concentration at breathing zone and in return air duct.

1066 ppm. For most of the time, the CO_2 level was below 1000 ppm when the CO_2 based demand control strategy was applied. Fig. 3 shows the typical CO_2 profile in the lecture theatre. The outdoor CO_2 level was found to vary from 350 to 400 ppm in our measurements. The indoor CO_2 level was a strong function of the number of occupants as occupants were the predominant CO_2 sources inside the lecture theatre. While there were no occupants in the lecture theatre, the CO_2 level was found to range from 350 to 400 ppm, almost the same as the outdoor CO_2 level. When the lecture theatre was occupied, even though there were very few occupants, the CO_2 level increased rapidly to above 450 ppm. It was generally found that 50 ppm above the outdoor CO_2 level could be treated as the indication of the presence of occupants. By doing so, sensors for detecting the presence of occupants can be avoided which could make the control simpler. This is acceptable for ventilation control while the required control accuracy is not too high. As the return air duct is the most technical feasible location to put the sensors and the CO_2 level at the return air duct is not the same as that at the breathing zone due to shot circuit of the fresh air, the CO_2 level at the return air duct was also measured simultaneously and was compared to the indoor CO_2 level at the breathing zone. The results show that the CO_2 level at the return air duct could be fitted in a linear relationship with that at the breathing zone. Fig. 4 shows the correlation between the CO_2 level at the breathing zone and that at the return air duct. By using the least square method on 1146 sets of data gained during the occupied hours, the correlation was obtained in Eq. (1):

$$y = 1.07x - 35.68 \quad (R^2 = 0.97), \tag{1}$$

where y is the CO_2 level at the breathing zone and x is the CO_2 level in the air return duct and the unit is ppm (Fig. 3).

With the obtained correlation between the CO_2 level at the breathing zone and that at the return air duct, it is possible to use the return air duct CO_2 level as the control signal with a proper compensation via Eq. (1). However, Eq. (1) comes from the data collected in our experiments. The parameters are only valid for the arrangement of our particular lecture room setting. While used in other buildings and ventilation arrangements, Eq. (1) needs to be modified for different applications.

The TVOC and formaldehyde levels were found to be acceptable during the whole day. The highest TVOC level was about 2532.5 ug m^{-3} and the highest formaldehyde level was 48.9 ug m^{-3}. Both were lower than the draft upper limit of level 2 IAQ objectives listed by Hong Kong Environmental Protection Department [12] which are 3000 and 100 ug m^3, respectively. This indicates that the TVOC and formaldehyde sources were not very strong and the fresh air supply was enough to dilute them to acceptable levels.

A very high radon level was found every morning before the HVAC system was turned on and a few hours after the system was turned off in the late evening. One typical radon profile in the lecture theatre is shown in Fig. 3. It was found that the radon level accumulated during the non-occupied hours and decreased after the ventilation system was turned on. The radon level was very high after a night of non-occupied period. It took a few hours to bring the radon level down to an acceptable level. In our experiments, the highest radon level recorded was about 800 Bq m^{-3}, and the ventilation system took more than three hours to bring it down to 200 Bq m^{-3}. which was the upper limit of the acceptable radon level (Department [12]). Therefore, the occupants in the lecture theatre were exposed to a radon level higher than 200 Bq m^{-3} for more than three hours. This showed that only CO_2 based demand control ventilation was not able to guarantee all the non-occupant-related indoor air pollutants to be kept at an acceptable level. As the exposure to a high radon level is associated with high lung cancer risk, this situation was not very acceptable.

According to Chao. et al.'s work [13] in Hong Kong, the indoor radon mainly comes from the building materials. The reason is that the building materials in Hong Kong are usually made of granite and the radon emanation rates of these materials are as high as about 9–12.96 Bq m^{-2} h^{-1} [14,15], which are much higher than those in other countries which in general are 0.52–2.86 Bq m^{-2} h^{-1}. Assuming that the indoor radon only comes from the surface of the building materials and the outdoor air and the radon emanation rate of the building materials are kept constant, with the mass balance equation, the time variation of the radon level in the lecture theatre is given by

$$V\frac{dC_i}{dt} = EA - \lambda VC_i - Q(C - C_o) \tag{2}$$

then,

$$C_i(t) = \frac{EA + QC_o}{\lambda V + Q}(1 - e^{-t/T}) + C_{i0}e^{-t/T}, \tag{3}$$

where C_i is the indoor radon concentration, C_o is the outdoor radon concentration, C_{i0} is the indoor radon concentration at the moment when the ventilation system is turned on, E is the average radon emanation rate of the building materials in the indoor environment, A is the area of the materials that emits radon, Q is the ventilation rate of the premises, λ is the radon decay constant, V is the effective volume of the premises, t is the time and T is the time constant of the system given by.

$$T = \frac{V}{V\lambda + Q}, \tag{4}$$

If there are only a few people in the lecture theatre, the fresh air supply rate will be very low when a CO_2 based demand control ventilation strategy is used. Under this situation, from Eq. (3), we can see that the radon level may be higher than the acceptable level for a long period of time. From the experimental results and Eq. (3), we can see that there were two reasons that caused the occupants exposed to a high radon concentration for a relatively long period of time. One was the extremely high radon level accumulated during the non-occupied hours and the other was the low fresh air supply rate which might not be enough to bring the radon level down to an acceptable level within an acceptable period of time. However, besides radon, this conclusion was also valid for other non-occupant-related indoor air pollutants if their emanation rates were high in some buildings. Therefore, in the development of the demand control ventilation strategy, besides CO_2, the non-occupant-related indoor pollutants levels should also be taken into account while supplying fresh air to the indoor environment and pre-purging should be considered to prevent the non-occupant-related pollutants from accumulating to extremely high levels.

In our experiments, the outdoor radon level was measured every day. It was found to be very low, ranging from 6 to 14 Bq m^{-3}. With such a small magnitude and variation, compare to the indoor radon level that often could be more than one hundred Bq m^{-3}, the outdoor radon level can be treated as a constant while solving Eq. (2). Eq. (2) can be used to estimate the radon emanation rate from building materials. Taking integration on both sides of Eq. (2) over time, it follows that

$$\int_{t_0}^{t_m} EA\,dt = \int_{C_{i0}}^{C_{im}} V\,dC_i + \int_{t_0}^{t_m} \lambda VC_i\,dt + \int_{t_0}^{t_m} Q(C_i - C_o)\,dt, \tag{5}$$

where t is the integration time, C_{i0} is the indoor radon concentration at time t_0 and C_{im} is the indoor radon concentration at time t_m.

With the measured indoor and outdoor radon levels and the ventilation rates which were measured by tracer gas decay technique, the radon emanation rate, E, of the building material inside the lecture theatre was estimated using Eq. (5). The radon emanation rate of the building materials in the lecture theatre was found to range from 398 to 478 Bq m^{-3} h^{-1} with an average of 424 Bq m^{-3} h^{-1}.

For the same reason as CO_2, the radon level in the return air duct was also measured and compared with that at breathing zone. It was found that the radon level in the return air duct fitted in a linear relationship with that at the breathing zone. With 500 sets data that was measured with an interval of 30 min in both the occupied hours and non-occupied hours, the correlation between the radon level in the air return duct and that at the breathing zone was obtained from and is shown in Eq. (6):

$$y = 0.79x + 152.71 \quad (R^2 = 0.86), \tag{6}$$

where y is the radon level at the breathing zone and x is the radon level at the return air duct, the unit is Bq m^{-3}.

4. Details of the demand control ventilation strategy

Based on the findings in the site measurements, a new type of dual-mode demand control ventilation strategy was developed, which uses both the occupant-related and non-occupant-related pollutant concentration as the control signals. As there are many non-occupant-related indoor contaminants and it is impossible to monitor all of them, one dominant contaminant, which requires the greatest amount of fresh air to dilute to an acceptable level, is selected as the control signal in our control strategy. From our former site measurements, radon was found to be the dominant indoor pollutant in the lecture theatre. Before the radon was diluted to an acceptable level, other non-occupant-related pollutants such as TVOC and formaldehyde had already been diluted to acceptable levels. Therefore, in our research, radon level is selected as a control signal to indicate the demand of fresh air to dilute the non-occupant-related indoor air pollutants. However, in other cases, the dominant non-occupant-related indoor pollutant should be identified via a site measurement. It may be TVOC, formaldehyde or other non-occupant-related indoor pollutants. The goal is to identify the pollutant that can be used to indicate the demand of fresh air to dilute all the non-occupant-related indoor pollutants. Besides the non-occupant-related indoor air pollutants, the occupant-related pollutants also need to be controlled. CO_2 is used as the indicator in our control strategy as in traditional demand control ventilation strategy. By controlling CO_2 and the dominant non-occupant-related pollutant to the desired levels, most of the other occupant-related and non-occupant-related indoor air pollutants can be maintained at acceptable levels.

This dual-mode demand control ventilation strategy mainly includes two operation modes. One is the real time modulation mode and the other is the purging mode. The modulation mode is used while there are occupants in the premises. Its objective is to control the fresh air supply rate so that an acceptable indoor air quality can be maintained during all occupied hours. The purging mode is used while the premises are not occupied. Its objective is to bring the non-occupant-related pollutants to acceptable levels before the premises are reoccupied after a long non-occupied period of time.

In this demand control ventilation strategy, the CO_2 level is monitored all the time to determine whether there are occupants in the premises. If occupants are detected, the control strategy will be switched to the modulation mode. Otherwise, the control strategy will be switched to the purging mode. If the level of the dominant non-occupant-related indoor pollutant, radon, is found to be so high that at least one hour is needed to bring the radon down to an acceptable level, the purging sequence will be started. In addition, the demand control strategy has the function that the purging sequence will be started 1 h before the premises are occupied after a long non-occupied period to ensure acceptable non-occupant-related indoor pollutants levels even at the very beginning of the occupied hours. If no purging sequence is triggered during the non-occupied hours, the demand control system will shut down the fresh air intake for the purpose of energy saving during non-occupancy. The flow chart of this demand control strategy is shown in Fig. 5 and the components of the strategy are discussed as follows:

4.1. *Definition of set points*

There are two set points in this demand control strategy: the CO_2 and radon levels. In our control strategy, the CO_2 set point is selected so that the outdoor air supply rate per person can meet the requirement listed in ASHRAE 62-1999 [9].

By a mass balance equation under equilibrium condition, with the outdoor air flow rate per person as V_o, the indoor CO_2 concentration, $C_{sco2,}$ can be expressed as

$$C_{sco2} = C_{oco2} + N/V_o \tag{7}$$

where C_{oco2} is the outdoor CO_2 concentration, N is the CO_2 generation rate per person and V_o is the outdoor air flow rate per person.

Eq. (7) is based on the rationale that the air in the room is well mixed and if the outdoor CO_2 level is 300 ppm and the occupants are sedentary, the indoor CO_2 level under equilibrium condition will be 1000 ppm. This provides the rationale behind many industrial practices that the indoor CO_2 level is recommended to be kept under 1000 ppm to represent a condition of acceptable indoor air quality. The recent version of ASHRAE 62-1999 has changed the statement by saying that when only dilution ventilation is used to control indoor air quality, an indoor to outdoor differential concentration of CO_2 not greater than about 700 ppm indicates comfort (odor). A practical concern here is that if a differential CO_2 level is needed rather than an absolute one as the set point, an extra CO_2 monitor is required outdoors to monitor the ambient CO_2 level. Moreover, our measurement in the preliminary phase study has shown that outdoor CO_2 level varied from 350 to 400 ppm and is fairly steady. It should be noted that our CO_2 monitor has an accuracy level of 50 ppm. We thus think it may be better if we keep the CO_2 set point at 1000 ppm rather than looking for a floating one. Another reason that we use 1000 ppm as the set point is that 1000 ppm CO_2 level has also been defined as the recommended good practice level (classified as Level 2 in a two-level system) in the newly established indoor air quality guidance notes published by the Hong Kong Environmental Protection Department [12].

An indoor radon level of 200 Bq m^{-3} is recommended by the Hong Kong Environmental Protection Department as the Level 2 criterion in the newly established guidance notes

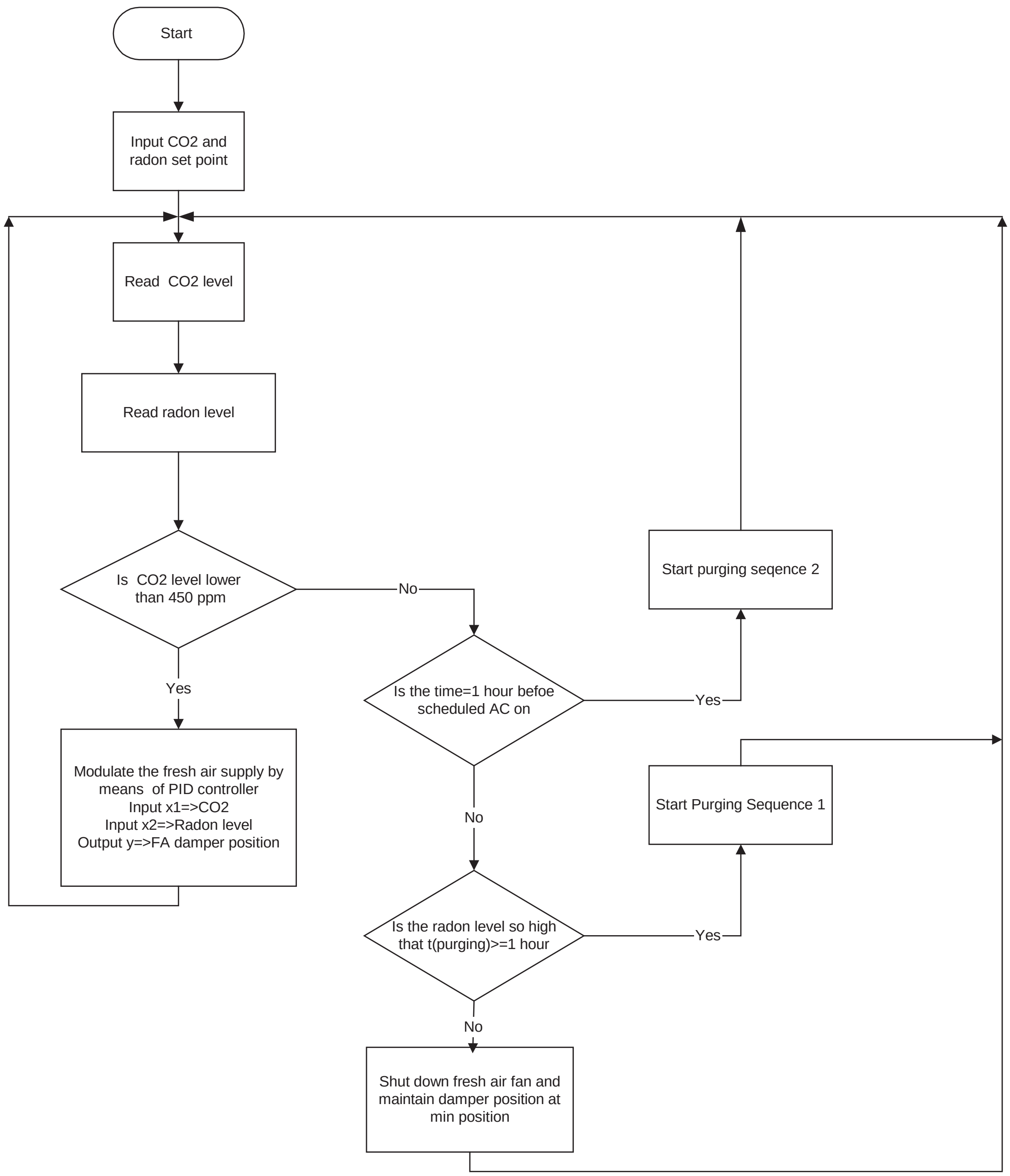

Fig. 5. The flow chart of the CO_2 and radon based demand control ventilation strategy.

[12] for public health. and is thus chosen as the set point in our control algorithm.

4.2. *Determination of presence of occupants*

The presence of occupants is the most crucial factor to determine in which mode the control system should be operated. CO_2 level is used to determine the occupancy since it is a good bio-effluent indicator for representing the presence of occupants. As shown in the site measurement, the CO_2 level is very sensitive to the presence of occupants and 50 ppm above the outdoor CO_2 level can accurately indicate the presence of the occupants even though there are only a few occupants in the premises. Therefore, in the control strategy, 50 ppm above the outdoor CO_2 level is selected as the threshold to determine the presence of occupants. In our case, this threshold is 450 ppm, since the maximum outdoor CO_2 level was found to be 400 ppm and varied very little during day or night.

4.3. *Location of the sensors*

As thorough mixing can never be fully achieved in buildings, the most important point is to achieve an acceptable

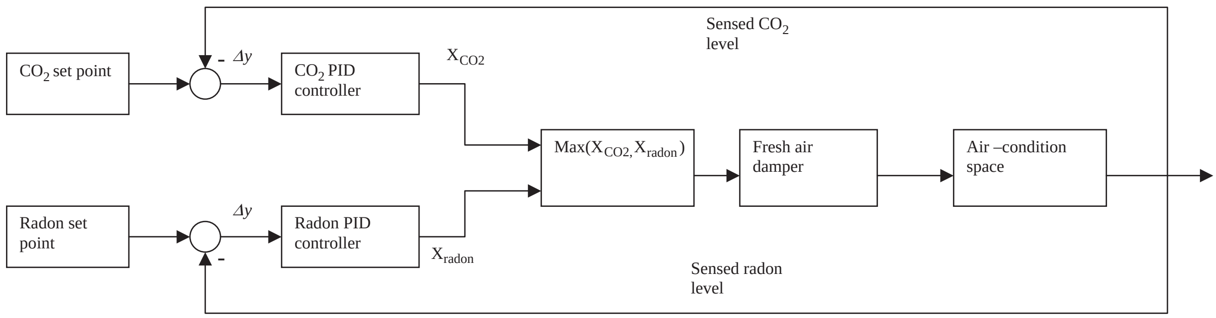

Fig. 6. Flow chart of the modulation mode.

indoor air quality in the occupant's breathing zone. Therefore the best location for mounting the CO_2 sensor and the radon sensor is at the occupants' breathing zone. However, these sensors usually cannot be located in the breathing zone for practical reasons, as they will obstruct the activities of the people in the room and the CO_2 reading will be unreliable if it is located too close to the occupants. A technically feasible location is to put the sensors in the return air ductwork. However, part of the return air is the by-pass fresh air due to short circuiting, and the CO_2 and radon levels are not the same as those in the breathing zone. In this control strategy, correlations between CO_2 and radon levels at the return air duct and at the breathing zone are used to compensate for the levels measured at the air return duct. The correlations should be obtained for different applications before the use of this control strategy as they are application specified.

4.4. *Modulation mode*

While there are occupants in the premises, the fresh air supply rate should be modulated according to the actual occupancy level and the radon level so that an acceptable indoor air quality can be obtained and no over-ventilation occurs. That is to say, the fresh air intake should be accurately controlled so that the indoor air quality reach an acceptable level. To achieve this goal, several control methods can be used such as the on/off control, P, PI, PID control and fuzzy control. Generally, the fuzzy control is used in very complicated systems or where it is difficult to handle by traditional control strategy. While using the fuzzy control, an expert knowledge library is needed. For different ventilation systems and buildings, the knowledge library may need to be updated for special application. As most of the ventilation systems are not very complicated and this dual-mode demand control ventilation strategy is for general purpose, fuzzy control is not used in our algorithm. In HVAC system, the on/off control, P, PI and PID control algorithm are the most commonly used because of their practicality. The on/off control is the simplest one but its control accuracy is not as good as the P, PI or PID control. In addition, using the on/off control, the fresh air flow rate will change too much, which may induce some fluctuation in the chilled water. Among the P, PI and PID control algorithms, with the fine-tuned PID parameters, PID control has the best control performance in its stability, static error and response time. Therefore, in the modulation mode, PID control algorithm is used to modulate the fresh air intake. The modulation mode is composed of two PID controllers: CO_2 PID controller and radon PID controller. The CO_2 PID controller is used to cater for the actual occupancy and control the fresh air supply to meet the requirement of comfort (odor). The radon PID controller is used to keep acceptable levels of radon as well as the other non-occupant-related pollutants during occupied hours. The outputs of both PID controllers are the fresh air damper positions, which are determined according to the PID algorithm as expressed by Eq. (8). The system will select the larger one as the system output. Fig. 6 shows the schematic of the modulation mode.

$$X(k) = K_p \cdot \Delta y(k) + K_d[\Delta y(k) - \Delta y(k-1)] + K_i \cdot \sum_{j=1}^{k} \Delta y(j), \quad (8)$$

where, $X(k)$ is the fresh air damper position calculated according to the 1st to kth sampled CO_2/radon levels, K_p is the proportional parameter, K_d is the differential parameter, K_i is the integral parameter and $\Delta y(k)$ is the difference between the CO_2/radon setpoint and the kth sampled CO_2/radon level.

4.5. *Purging sequence*

As mentioned before, the accumulated extremely high levels of non-occupant-related pollutants is one of the reasons that the occupants are exposed to undesired indoor environment. Two purging sequences are designed to reduce the accumulation of non-occupant-related pollutants during the non-occupied period so that acceptable non-occupant-related indoor pollutants levels can be obtained just before the indoor environment is occupied.

During the purging sequence, fresh air is introduced into the premises with the maximum flow rate of the ventilation system. By diluting the dominant non-occupant-related pollutant, radon in our case, to acceptable level, other non-occupant-related pollutants can be diluted to acceptable levels as enough fresh air is brought into the premise. By Eq. (3), the time needed by the purging sequence to bring the radon down to an expected level C_{max} is given by Eq. (9):

$$t_{pg} = -T \ln \left(\frac{C_{max} - \dfrac{EA + Q_{max} C_o}{\lambda V + Q_{max}}}{C_{i0} - \dfrac{EA + Q_{max} C_o}{\lambda V + Q_{max}}} \right) \quad (9)$$

where t_{pg} is the duration of the purging sequence, Q_{max} is the maximum ventilation rate of the premises, C_{i0} is the indoor radon concentration at the beginning of the purging sequence, C_o is the outdoor radon concentration, E is the average radon emanation rate of the building materials in the premise, and both E and C_o can be determined by a pre-conducted measurement.

4.5.1. *Purging sequence 1: One-hour purging sequence*

A 1-h purging sequence is designed to cater to the situation in which the premises are unoccupied for a relatively long period of time. During the non-occupied hours in the evening or over the weekend, the radon level is allowed to exceed the set point for the purpose of energy saving as there is no occupant in the premises. However, the radon level should be controlled so that the premise can be safely reoccupied. In our algorithm, the highest radon level allowed during the non-occupied hours is the radon level that can be brought to the set point with the maximum ventilation rate within one hour. By keeping the radon level below this limit, an acceptable level can be obtained just before the occupied hours by purging sequence 2, which will be discussed in the next section. In addition, if occasionally the premises are reoccupied before the scheduled system turn-on time, the radon PID controller can also bring this radon level down to an acceptable level within a relatively short time. During non-occupied hours, the system monitors the radon level closely. According to Eq. (9), the system is capable of determining how long it will take to reduce the radon concentration to a permissible level. If the detected radon level needs more than one hour to be brought down to the set point, the purging sequence is activated.

4.5.2. *Purging sequence 2: scheduled purging*

In order to ensure that the occupants will not be exposed to undesirable levels of radon and other non-occupant-related pollutants in any circumstance, there is a scheduled purging sequence, which starts one hour before the scheduled system turn-on time and continues for 1 h. The radon level after purging sequence 2 is given by

$$C_{p2} = \frac{EA + QC_o}{\lambda V + Q}\left(1 - e^{-3600/T}\right) + C_{i0} e^{-3600/T}, \quad (10)$$

where C_{p2} is the radon level after purging sequence 2 and C_{i0} is the radon level before purging sequence 2.

C_{i0} will never exceed the critical level, which needs more than one hour to be brought down to the set point as discussed in Section 4.5.1 and the radon level will be maintained lower than the set point after carrying out purging sequence 2 early in the morning. Combining purging sequences 1 and 2, we can ensure an acceptable radon level at the beginning of the occupied period.

4.6. *Shutdown of the fresh air intake*

While the premises are not occupied and no purging sequence is triggered, the demand control system will shut down the fresh air intake for energy saving.

5. Results and discussion for the performance of the dual-mode demand control ventilation strategy

5.1. *Indoor air quality*

During the experiments, major indoor air pollutants such as radon, CO_2, TVOC and formaldehyde were measured. Fig. 7 shows the typical time variations of CO_2 and radon levels, which indicate the demand of fresh air to dilute the occupant-related and non-occupant-related indoor air pollutants, respectively. From Fig. 7, it can be seen that the radon level continuously increased during the non-occupied hours. As the radon emanation rate in the lecture theatre was not so high, the case when more than one hour is required to bring the radon level down to 200 Bq m^{-3} was not found. However, this situation may occur in other buildings where the radon emanation rates are relatively higher and the ventilation rates are relatively lower. In the lecture theatre, the scheduled pre-purging, Purging sequence 2, started one hour before the occupied hours. From Fig. 7, we can see that after starting purging sequence 2, the indoor radon level decreased rapidly. At the beginning of the occupied hours it had decreased to about 200 Bq m^{-3}. During the lecture hours, by the radon PID controller, the radon level was never found to exceed 200 Bq m^{-3}, which was acceptable as the Hong Kong Environmental Protection Department had set the 200 Bq m^{-3} as the upper limit of Level 2 in the newly established guidance notes [12]. The experimental results show that the pre-purging plus the real-time modulation can efficiently prevent the occupants from exposing to an undesirable radon level. In most of the lecture hours, the CO_2 level was found to be below or around 1000 ppm. The highest CO_2 level was about 1180 ppm. By controlling the CO_2 at such levels, about 8 l/s per person fresh air was brought into the lecture theatre, which was just enough to dilute the occupant-related indoor air pollutants to acceptable level. With controlling CO_2 and the dominant non-occupant-related indoor pollutant, radon, to acceptable levels by bringing proper amount of fresh air into the lecture theatre, other indoor air pollutants were also at the acceptable levels. During the lecture hours, the highest TVOC was 2014.5 ug/m^3, which was lower than the upper limit of Level 2 as required by HKEPD. The highest formaldehyde

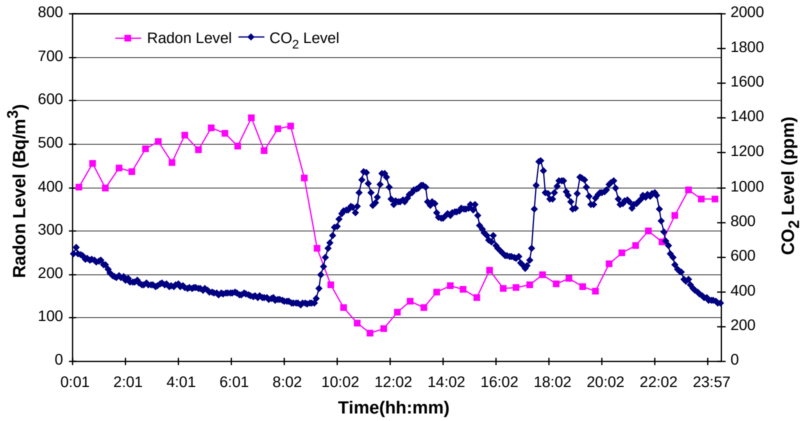

Fig. 7. Typical radon and CO_2 profiles in the lecture theatre while using dual mode demand control ventilation strategy.

Table 1
Result of the questionnaire survey on indoor air quality

Rate	Very good	Good	Fairly good	Fair	Slightly Poor	Poor	Very Poor
Percentage	0.00%	28.07%	9.69%	52.40%	6.14%	1.85%	1.85%

level is 36.7 ug m^{-3} and is also lower than the upper limit of Level 2.

Besides the indoor air quality measurement, a questionnaire survey was also conducted at the same time to investigate how the occupants think about the indoor air quality while using our dual-mode demand control ventilation strategy. During the experiments, totally 500 questionnaires were handed out and 382 were collected back. The statistic result is shown in Table 1. Very few occupants thought that the indoor air quality was very good or very poor. About 50% of them thought that the air quality in the lecture was fair. Another 28% of the occupants thought that the air quality was good. Totally more than 90% of them thought that the indoor air quality was acceptable. That is to say, a substantial majority of the occupants did not express dissatisfaction on the indoor air quality. As defined in ASHRAE 62-1999, combining with the results of the indoor air quality measurement, an acceptable indoor air quality was obtained by using our dual-mode demand control strategy. However, this good performance was partly benefited by the accurate correlations between CO_2 and radon levels at the return air duct and at the breathing zone gained from the pre-measurement. A pre-measurement is necessary to obtain the correlations for different applications before the use of this control strategy.

5.2. *Energy consumption*

Besides indoor air quality, the performance of the dual-mode demand control ventilation system on energy saving was also studied. The Yamatake energy metering system was used to record the energy consumed by the AHU while using the dual mode demand control system. For the purpose of comparison, we also ran the original fixed-rate ventilation system at selected days when the occupancy levels were almost the same as that when we conducted the dual mode demand control ventilation. The energy consumption under the fixed-rate ventilation was also recorded.

The experiments covered the summer vacation period and the regular semester period. In the summer vacation period, it was hot and humid. The number of occupants was fewer and varied a lot. Under such a circumstance, the dual-mode demand control ventilation system might save the maximum amount of energy as the fresh air requirement was relatively low and conditioning the fresh air may occupy a larger pie of total energy consumption in the whole HVAC system. During the regular semester period, which was the normal situation, the number of occupants was more and the fresh air requirement also increased. The energy saved was not as much as that in the summer vacation in term of percentage.

Table 2 shows the energy consumption of the HVAC system in the summer vacation. Both the results of using our dual-mode demand control ventilation strategy and the original fixed-rate ventilation control were presented. From Table 2, we can see that the average of the daily mean cooling power during the days while using the dual-mode demand control ventilation strategy was 13.3 KW and it was 22.9 KW while using the original fixed-rate ventilation. About 42% of the daily cooling energy was saved. However, there might be an overestimation on this figure as the energy consumption might be influenced by many factors such as the indoor/outdoor conditions, the occupancy levels and so on. We can see that from the fresh air enthalpies in

Table 2
Energy consumption during the summer vacation period

Demand control ventilation strategy			Fixed rate ventilation control strategy		
Time	Average fresh air enthalpy (KJ Kg^{-1})	Average cooling power (KW)	Time	Average fresh air enthalpy (KJ Kg^{-1})	Average cooling power (KW)
1st Day	61.3	12.6	1st Day	64.1	24.1
2nd Day	61.7	14.1	2nd Day	62.9	22.4
3rd Day	62.3	13.6	3rd day	62.2	21.5
4th Day	61.8	12.9	4th Day	64.6	23.6
Total	61.7	13.3	Total	63.5	22.9

Table 3
Energy consumption during the regular semester period

Demand control ventilation strategy			Fixed rate ventilation control strategy		
Time	Average fresh air enthalpy (KJ Kg^{-1})	Average cooling power (KW)	Time	Average fresh air enthalpy (KJ Kg^{-1})	Average cooling power (KW)
1st Day	63.9	28.1	1st Day	58.1	29.3
2nd Day	65.3	27.8	2nd Day	66.3	32.6
3rd Day	67.7	24.9	3rd day	66.1	30.1
4th Day	68.1	28.5	4th Day	62.2	29.1
5th Day	67.4	26.3	5th Day	65.5	30.3
Total	67.7	26.6	Total	63.6	30.3

the Table 2 that while using these two ventilation control strategies, the outdoor conditions were not the same, though the indoor temperature and indoor relative humidity were controlled to be the same and the experiments were conducted under almost the same the occupancy level. On the 3rd day of using the dual-mode demand control ventilation strategy and the 3rd day of using fixed-rate ventilation control, the fresh air enthalpies were almost the same. By comparing the energy consumption in these two days, it can be found that about 35% of the cooling energy was saved by using the dual-mode demand control ventilation system. Assuming that the daily cooling energy consumed in this lecture theatre during the summer vacation was 210 KWh, about 73.5 KWh cooling energy could be saved. As the coefficient of performance of the air conditioning system was about 3.5, 73.5 KWh cooling energy corresponds to about 21 KWh of electrical energy. Taking into account the additional electrical energy consumed by fans for the purging sequence, which was about 4 KWh because the fan power of the AHU was 4 KW and only purging sequence 2 acted, there was still about 17 KWh electrical energy, i.e. 28.3% daily electrical energy, that could be saved. Table 3 shows the energy consumption in the regular semester period by using the dual-mode demand control ventilation strategy and the fixed-rate ventilation. From Table 3, we can find that 12.3% of the total cooling energy was saved. Assuming that the daily cooling energy consumed during the regular semester period was 350 KWh and taking into account the additional energy consumed by the fan for purging sequence, 8.3% of the total electrical energy was saved. The results show that our dual-mode demand control ventilation strategy has an excellent performance on energy saving while maintaining an acceptable indoor air quality.

6. Conclusions

In this paper, the results of a series of site measurements conducted at a typical lecture theatre of the Hong Kong University of Science and Technology are reported. The experimental results show that using only CO_2 based demand control ventilation was not able to guarantee all the non-occupant-related indoor air pollutants at acceptable levels. Occupants may be exposed to undesirable indoor air contaminants for a relatively long period of time. The main reasons were that the non-occupant-related indoor air pollutants might accumulate to very high levels during the non-occupied period and the fresh air supply rate during the occupied hours was determined only based on the occupancy regardless of the non-occupant-related indoor air pollutants levels. Based on the findings in the site measurement, a new type of demand control ventilation strategy using CO_2 and one non-occupant-related indoor air pollutants level as control signals was developed. In our case, radon was identified as the dominant non-occupant-related indoor air pollutant. In order to verify the performance of the developed dual-mode demand control ventilation strategy, experiments were conducted in a lecture theatre. Both the performances on indoor air quality and energy consumption were studied. The results show that an acceptable indoor air quality could be obtained by using our dual-mode demand control ventilation strategy. Comparing with the original fixed-rate ventilation control strategy, about 8.3–28.3% of the daily electrical energy was saved.

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