Improvement in demand-controlled ventilation simulation on multi-purposed facilities under an occupant based ventilation standard

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Abstract

The objective of this paper was to find an effective way of improving demand-controlled ventilation (DCV) simulation performed under an occupant based ventilation standard established in many countries. Two attractive DCV approaches, CO$_2$–DCV and RFID–DCV, were applied to DCV simulations for a theoretical public assembly space served by a dedicated outdoor air system (DOAS) with an enthalpy recovery device. A numerical model for predicting the real-time occupant number, required ventilation amount, CO$_2$ and formaldehyde (HCHO) concentrations under given conditions was developed using a commercial equation solver program. The current ventilation standard used in Korea was applied as a case of occupant based ventilation standards. It was found that the current standard might cause unstable DCV simulation results, especially under CO$_2$–DCV. This is because the ventilation rate (per person) indicated in the standard is the sum of the outdoor air required to remove or dilute air contaminants generated by both occupants and the buildings themselves, and not a pure function of occupant numbers. Finally, it makes DCV control unstable when ventilation flow is regulated only by the number of occupants. In order to solve this problem, the current occupant based ventilation standard was modified as a form of ASHRAE Standard 62.1-2007 showing good applicability to various DCV approaches. It was found that this modification enhances applicability of the current ventilation standard to CO$_2$–DCV significantly and can maintain acceptable HCHO concentrations during the entire time of operation. Fan energy reduction can also be expected from DCV operations.

1. Introduction

In order to enhance the indoor air quality in multipurpose facilities, the existing ventilation standard has been revised in South Korea [1]. The new ventilation standard defines minimum ventilation rates per person for various facilities in which several undesirable air quality problems caused by insufficient ventilation have been continuously reported over the past decade [2–6]. In early 2000, after it became a well-known fact that formaldehyde (HCHO) and Volatile Organic Compounds (VOCs) emitted from conventional building materials are major sources of various indoor air quality problems and physical symptoms [7–10], the Korea Institute of Construction Technology (KICT) investigated the indoor air quality of many different types of multipurpose facilities, and proposed minimum required ventilation rates for each facility which can maintain indoor HCHO concentration under the limit of 100–120 $\mu$g/m$^3$ recommended by the World Health Organization (WHO) [11].

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The minimum ventilation rates of the revised standard (Table 1) are 10–15% higher than those of the previous versions, and the 24-h operation of a mechanical ventilation system is allowed if it is required.

An increase of the minimum ventilation rate may solve traditional air quality problems experienced in many buildings. However, energy consumption induced by increased outdoor air intake should be resolved. As an effective solution, the use of a high performance ventilation system integrated with a total energy recovery device (e.g. enthalpy wheel) has been suggested [12–14].

On the other hand, controlling the ventilation system to supply an accurate amount of outdoor air based on real-time ventilation demand may also be a good strategy for saving energy [15–17]. This is called demand-controlled ventilation (DCV). As for the buildings with fluctuating occupant number (e.g. multi-purposed facilities, schools, etc.), DCV will be an effective way of saving energy in mechanical ventilation [18,19].

The most popular way of determining real-time ventilation demand is to track the number of occupants. Once the real-time occupant number is known, the amount of outdoor air induced at the air handler is adjusted based on the minimum ventilation rate per person recommended by the current ventilation standard. Many countries including South Korea have a “per person” based ventilation standard. It is a straightforward and reasonable way to define ventilation rates if indoor air contamination is mainly caused by occupants. On the other hand, ASHRAE Standard 62.1-2007 [20], the ventilation standard of United States, defines minimum ventilation rates as two different components in the Ventilation Rate Procedure (VRP): one is people component and the other is building component. The former is the minimum outdoor air (per person) diluting or removing human generated air contaminants, the latter is the required ventilation (per unit floor area) for contaminants generated by various building materials. It is based on the fact that people and building materials have different contaminant generation mechanisms.

The objective of this paper is to find an effective way to enhance the performance of DCV control integrated with the current Korean ventilation standard in multi-purposed buildings in South Korea. By comparing the adaptability of the two different ventilation standards (i.e. Ventilation standard of Korea and ASHRAE Standard 62.1-2007) to existing DCV strategies, critical factors that should be considered in current Korean ventilation standard for better adaptability to DCV are suggested.

2. Demand-controlled ventilation (DCV)

DCV is a ventilation rate control strategy to provide exact amount of ventilation air to each space based on the real-time ventilation demand. In HVAC practices, a simple and inexpensive closed loop control system consists of CO2 or occupancy sensors, programmable controllers and ventilation damper actuators (pneumatic or electric) are commonly used for DCV. A number of DCV approaches have been proposed to account for actual occupancy levels and provide the ventilation rates corresponding to actual rather than design occupancy. These include following:

2.1. Occupant schedule

This method uses a pre-defined time-based occupancy schedule in DCV control. If the transient behavior of occupancy level for each day of the week can be easily acquired by a simple statistical manner, one may use this approximate occupant schedule for controlling the outdoor air intake rate. This approach is the most economical way of DCV for the buildings with predictable occupancy patterns (e.g. office buildings).

2.2. Use of infrared sensor

An infrared sensor installed in a room perceives the space is occupied or unoccupied (though not how much). The ventilation system is controlled on-off based on the sensor’s binary signal and supplies design outdoor airflow when the space is occupied. This method is a simple and effective, but the possibility of over ventilation always exists because it is not controlled based on the number of occupants.

### Table 1

<table>
<thead>
<tr>
<th>Type of facility</th>
<th>Ventilation rate (m³/h-person)</th>
<th>Special note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underground facilities</td>
<td>Underground subway station 25 or more 36 or more</td>
<td>2000 m² or more gross floor area</td>
</tr>
<tr>
<td>Museum/Art gallery, Public assembly facilities</td>
<td>29 or more 29 or more</td>
<td>3000 m² or more gross floor area</td>
</tr>
<tr>
<td>Sales and business facilities, Transportation terminals</td>
<td>29 or more 29 or more</td>
<td>2000 m² or more gross floor area</td>
</tr>
<tr>
<td>Medical facilities</td>
<td>36 or more 36 or more</td>
<td>2000 m² or more gross floor area</td>
</tr>
<tr>
<td>Library, Daycare, and Public welfare facilities</td>
<td>36 or more 36 or more</td>
<td>1000 m² or more gross floor area</td>
</tr>
<tr>
<td>Indoor parking lots</td>
<td>27 or more 27 or more</td>
<td>2000 m² or more gross floor area</td>
</tr>
<tr>
<td>Public healthcare facilities</td>
<td>25 or more 25 or more</td>
<td>500 m² or more gross floor area</td>
</tr>
</tbody>
</table>
2.3. CO₂-based approach

This approach has been attracting many interests over the past decade [21–23]. The number of occupants can be estimated in real-time indirectly by monitoring indoor CO₂ concentration variations. With the assumption that occupants are the major source of CO₂ generation, one may pursue approximate transient variation of occupant numbers by considering CO₂ generation rate per person. The outdoor air intake rate is adjusted based on the estimated real-time number of people. Carbon dioxide sensors are installed in each room or somewhere inside of main return duct. For maintaining good system performance, CO₂ sensors need continuous recalibration and maintenance after installation.

2.4. Direct measurement of the number of occupants

In principle, by installing a sensor perceiving a person going in and out of each room, the exact number of people can be directly determined. However, this approach could not have been realized in actual buildings because of the lack of economical means to track people going in and out of a space. Recently, the use of radio frequency identification (RFID) technology in building services areas has been suggested [24]. By attaching a radio frequency identification (RFID) tag on a personal identification card for example, the exact number of occupants in each room can be traced. The outdoor air intake rate is adjusted based on this exact number. With the rapid development of various ubiquitous technologies for buildings, it is expected that this type of DCV will be more widely used in near future.

On the other hand, a ventilation system can be controlled to maintain the concentration of a specific air contaminant below the certain upper limit provided by a relevant standard. But this approach is usually applied to special cases (e.g. laboratories, hospitals, and industrial plants), so it is excluded in this study.

3. DCV simulation

It is assumed that DCV is performed for a space in a multi-purposed building in South Korea. The number of people is acquired by two different approaches. One is to use indoor CO₂ concentration variations and the other is direct measurement. The Korean ventilation standard is applied first to DCV simulations, and then the results are compared with those for the ASHRAE Standard 62.1–2007 referenced in many countries to make their ventilation standards or for related researches. Analyzing the results for the two different ventilation standards, will reveal important factors for improving the adaptability of the current Korean ventilation standard for multi-purposed buildings to the DCV method.

3.1. Simulation model

A 10 m × 10 m × 4 m space in a multi-purposed building (e.g. art gallery or museum) is selected for DCV simulations. A dedicated outdoor air system (DOAS) with a total energy recovery device [25] supplies the required ventilation air into the space (Fig. 1). The outdoor air intake rate is adjusted based on a given DCV strategy. Design occupant density is set to 40 people per 100 m² as indicated by ASHRAE Standard 62.1. Infiltration through exterior envelope is not considered on the assumption that the model space is an interior space.
The ambient CO₂ concentration is set to 300 ppm. And the exhaust air is balanced with the supply air. The minimum ventilation rate recommended by the Korean ventilation standard for the given space is 29 m³/person-h. The ASHRAE Standard indicates 13.7 m³/person-h as a people component and 1.1 m³/m²-h as building component ventilation rate. Simulation models are developed using commercial equation solver software [29] by mathematically modeling characteristics of each DCV strategy. It is assumed that the number of people varies as shown in Fig. 2.

3.1.1. CO₂-based DCV

The CO₂-based DCV (or CO₂–DCV) method controls the ventilation airflow using the real-time occupant number estimated indirectly from the indoor CO₂ level variation. By considering the model space (Fig. 1) as a control volume, the ordinary differential equation, which expresses the transient behavior of CO₂ concentration, is derived (Eq. (1)).

\[
\frac{dC}{dt} = \frac{-Q_s(C - C_s)}{V} + \frac{G}{C_1}P.
\]

(1)

where \(V\) is the volume of the room, m³; \(C\) the indoor CO₂ concentration, m³/m³; \(C_s\) the CO₂ concentration of air supply, m³/m³; \(Q_s\) the amount of air supply, m³/min; \(dC/dt\) the time-variant change of CO₂ concentration, 1/min; \(P\) the number of occupants; and \(G\) is the amount of CO₂ emission per person, m³/min-person.

For getting the numerical solution, Eq. (1) is approximated using the finite different approach and solved for the number of occupants (Eq. (2)).

\[
P_n = \frac{1}{G} \left[ V \left( \frac{C_n - C_{n-1}}{\Delta t} \right) + Q_s(n(C_n - C_{n-1})) \right]
\]

(2)

where \(\Delta t\) is the time interval and \(n, n-1\) is the current and previous time step.

The CO₂ generation rate per person is set to 0.0003 m³/min for an adult for ordinary office work or light activity [16]. CO₂ sensors are located at outdoor air intake and inside the model space. It is assumed that occupants are the only source of indoor CO₂ generation and the room air is always in a well-mixed condition.

3.1.2. RFID–DCV

This method adjusts the amount of ventilation air based on the real-time number of occupants measured precisely by the RFID technology. It is assumed that each individual in the model space has a RFID admission ticket, so the hourly variation of occupant number shown in Fig. 2 can be traced exactly. This DCV approach has not been widely used compared with CO₂–DCV because of some issues required to be resolved such as high initial cost and protecting occupant privacy. However, it is expected that a solution to those issues will be found soon with the rapid advance of sensor and information technology.
3.2. Discussions

3.2.1. DCV with ASHRAE Standard 62.1-2007

In the case of the ASHRAE standard applied DCV, ventilation air to the space is the sum of two ventilation components; people and building components. The people component is the product of the real-time number of people and the minimum ventilation rate per person (i.e. 13.7 m³/ person-h). The building component is acquired by multiplying ventilation rate per unit floor area (i.e. 1.1 m³/m²-h) by the total floor area of the given space (i.e. 100 m²); that is, 110 m³/h. The number of occupants is estimated from the change of indoor CO₂ concentration in the CO₂–DCV case and precisely measured in the RFID–DCV case.

On the other hand, it is assumed that the DOAS is turned off during the unoccupied hours (i.e. from 21:00 p.m. to 6:00 a.m.) for energy savings. However, it would be good idea to maintain the building component ventilation continuously even at non-occupancy times for the removal or dilution of contaminants emitted from building itself.

Fig. 3 depicts DCV simulation results for ASHRAE Standard 62.1. The CO₂–DCV method tracks the number of occupants indirectly but very closely to the RFID–DCV case measuring the accurate number of occupants (Fig. 3a). As shown in Fig. 3b, both DCV approaches adjust ventilation airflow well enough based on the transient change of occupants. However, one may find that CO₂–DCV experiences delays in ventilation air control (Fig. 3b), while RFID–DCV does not. This is because the change of indoor CO₂ concentration does not occur instantaneously with the change of occupant numbers. When occupant number increases, the space is under-ventilated because the number of people is underestimated from the room CO₂ concentration changing slowly. Similarly, if the people decrease, the model space experiences over-ventilation caused by the over-estimated occupants from the indoor CO₂ built up during the previous hours (Fig. 3b and c).

However, as shown in Fig. 3, the impact of delays in CO₂–DCV is negligible. Consequently one may conclude that the ASHRAE Standard 62.1-2007 shows good applicability to both the CO₂ and RFID–DCV methods. Although the room CO₂ concentration is over 1000 ppm, the upper limit of the Korean standard, during some occupied hours (Fig. 3c), it may be acceptable under the current ASHRAE standard which does not indicate specific upper limit CO₂ concentration.

3.2.2. DCV with Korean ventilation standard

In the DCV under the current ventilation standard, the outdoor air intake rate is the product of the real-time number of occupants and the minimum ventilation rate per person (i.e. 29 m³/h-person) indicated by the standard. Contrary to the ASHRAE Standard 62.1, the Korean standard for multi-purposed facility defines the ventilation rate per person required to control contaminants emitted from both the people and the building itself. People and building components are not defined separately, while the ASHRAE Standard 62.1 does so. It is assumed that the ventilation system is turned off when there is no occupant.

Fig. 4 shows the results of DCV simulation for the current Korean ventilation standard. The predicted number of occupants in the CO₂–DCV case fluctuates severely and experiences an overshooting problem (Fig. 4a). Consequently, the amount of ventilation air adjusted for the number of people also shows extreme fluctuation in CO₂–DCV (Fig. 4b). The reason for the unstable ventilation control observed in the CO₂–DCV case is that the minimum ventilation rate (per person) indicated by the current standard is relatively high, so fluctuation of supply air causes the frequent change of the indoor CO₂ concentrations (Fig. 4c) and the overshooting problem in predicting the number of occupants using Eq. (2). This instability problem might be mitigated mathematically by adjusting solution time step (Δt) in Eq. (2) or using other solution methods (e.g. Runge–Kutta). In addition, in real HVAC practices, this type of instability would be resolved in some degrees by applying conventional P, PI or PID control loop. However, it is not a fundamental solution to this instability problem. Current ventilation standard itself would be the original reason for the problem as shown in Fig. 4. On the contrary to CO₂–DCV, RFID–DCV, which does not depend on indoor CO₂ variation in the estimated number of occupants, shows good controls in real-time ventilation adjustment and indoor CO₂ concentration for the entire time (Fig. 4c).

On the other hand, if the DOAS is simply on-off controlled using a binary infrared occupancy sensor, the space is over ventilated throughout the entire day (Fig. 4b), and the indoor CO₂ concentration is much lower than that of other DCV cases (Fig. 4c). In South Korea, the upper limit of indoor CO₂ concentration is under 1000 ppm [28], so one may conclude that CO₂ or RFID–DCV methods can operate the ventilation system more efficiently than the simple binary control.

3.2.3. Improvement of CO₂–DCV performance

From Fig. 4, one may conclude that applicability of the current Korean ventilation standard to CO₂–DCV should be improved for getting better DCV performance. The RFID–DCV method would be a good alternative to the CO₂–DCV approach in this case, but several technical, economical, and privacy issues should be resolved first. In the multi-purposed facility used by a great deal of unspecified people, the CO₂–DCV method tracking the number of occupants indirectly is still a practical solution for demand-controlled ventilation.

As discussed in Section 3.2.2, the major reason for undesirable fluctuating ventilation control in the CO₂–DCV case is that the current Korean ventilation standard is defined as total ventilation amount for treating both people and building generated contaminants simultaneously, although it is expressed as a function of the number of occupants only. To solve this problem, the current standard is modified to have two ventilation components; people and building components like the ASHRAE Standard 62.1. And then CO₂–DCV simulation is performed again to see whether the modification improves the DCV performance or not.
Fig. 3. DCV with ASHRAE Standard 62.1-2007.
Fig. 4. DCV with Korean Ventilation Standard.
3.2.3.1. Modification of the current ventilation standard. If the ASHRAE standard is applied to the model space under the maximum design occupancy, the design ventilation rate will be 658 m$^3$/h. About 16.7% of it (i.e. 110 m$^3$/h) is the building component, which should be supplied regardless of the number of occupants. The remaining (i.e. 548 m$^3$/h) is the people component, which should be adjusted by the real-time number of occupants.

On the other hand, when the current Korean ventilation standard is applied, the design ventilation airflow will be 1160 m$^3$/h. This design value is divided into two ventilation components as a form of the ASHRAE Standard; that is, 16.7% of the design flow (i.e. 194 m$^3$/h) is set to the building component ventilation. And the rest of the design airflow (i.e. 966 m$^3$/h) is considered the people component. Consequently, the modified ventilation rates based on the current Korean ventilation standard for the model space are 1.94 m$^3$/h-m$^2$ (building component) and 23 m$^3$/h-person (people component).

3.2.3.2. CO$_2$–DCV with modified ventilation standard. DCV simulations based on the modified Korean ventilation standard were performed for the model space. Fig. 5 shows that the performance of CO$_2$–DCV is significantly improved by the modified standard considering the building component and the people component separately. Undesirable fluctuations of the predicted number of occupants and ventilation airflow observed in CO$_2$–DCV with the original standard (Fig. 4a and b) are resolved as expected (Fig. 5a and b) because frequent change of indoor CO$_2$ concentration (Fig. 4c) is avoided by adjusting only the people component ventilation flow (Fig. 5c), and consequently the accuracy of occupant number prediction using Eq. (2) is improved.

Fig. 5 also shows that RFID–DCV provides good ventilation control performance even under the modified ventilation standard. From this observation, one may conclude that when the direct measurement of the real-time number of occupants is used, the DCV performance is not very sensitive to types of ventilation standard applied. Meanwhile simple on-off control method still over-ventilates the space during the occupied time (Fig. 5b and c).

3.2.4. DCV impact on indoor formaldehyde concentration

The formaldehyde (HCHO) concentration is commonly used as an objective indicator for evaluating indoor air quality and the level of safety from harmful contaminants generated by various building materials. In this study, the transient behavior of indoor HCHO concentration was investigated for the CO$_2$–DCV, RFID–DCV, and simple on-off control cases under the three different ventilation standards: the ASHRAE Standard 62.1, the current Korean ventilation standard, and the modified Korean standard.

The indoor HCHO concentration was predicted for each case by solving Eq. (2) numerically after switching CO$_2$ concentration to HCHO concentration. The background HCHO concentration was assumed to be 0.0036 mg/m$^3$, and the HCHO generation rate in the model space was set to 0.00812 mg/m$^3$-h by referring the open literature [26,27].

Fig. 6 depicts the simulation results of indoor HCHO concentration. When CO$_2$–DCV and RFID–DCV are performed under the current Korean ventilation standard, HCHO concentration decreases much faster from 8:00 a.m. to noon (i.e. the time when occupants increase) than those for other ventilation standards. Similarly, from 5:00 p.m. to 9:00 p.m., when the number of occupants decreases, indoor HCHO concentration increases quite rapidly. The current Korean ventilation standard is defined as a total outdoor air intake rate per person required to remove or dilute contaminants emitted from both occupants and building simultaneously, so the ventilation air supplied increases or decrease at large scale with the change of the number of occupants and it causes the rapid change of indoor HCHO concentration. In both CO$_2$–DCV and RFID–DCV with the current Korean ventilation standard, rapid increase of HCHO concentration under the low occupant number condition cannot be avoided as shown in Fig. 6. It would be the inherent drawback of "per person" based ventilation standard including current Korean ventilation standard.

As for DCV cases under the modified Korean standard, the change of indoor HCHO concentration is slowed down when the number of occupants changes (Fig. 6). This is because only the people component ventilation, which is relatively small, is adjusted for the occupant changes. One may also find in Fig. 6 that the indoor HCHO concentration is maintained at a lower level compared with the results for the original Korean ventilation standard because of the building component ventilation defined by the modification. The building component is supplied at constant rate during the entire operating time.

On the other hand, when the system is controlled on–off and supplies ventilation air indicated by the current ventilation standard, the indoor HCHO concentration can be maintained at the lowest level (Fig. 6) because the space is over ventilated during the occupied hours. This would be good in terms of indoor air quality, but it consumes more energy. CO$_2$–DCV and RFID–DCV methods maintain the indoor HCHO concentration within the acceptable level (i.e. 100 μg/m$^3$) even though less ventilation air is supplied. It means that DCV controls indoor air quality more efficiently.

Another important observation in Fig. 6 is that the ASHRAE Standard 62.1 can maintain indoor HCHO concentrations below the acceptable level, despite whether the ventilation air supplied to the model space is much less than those for the Korean standard applied cases. For example, when the model space is fully occupied, the ventilation airflow rate based on the ASHRAE Standard 62.1 is 658 m$^3$/h. It is only 56.7% of the Korean standard based ventilation rate (i.e. 1160 m$^3$/h), but the indoor HCHO concentration is maintained below the upper limit in both the CO$_2$ and RFID–DCV cases. This result indicates that high ventilation rate per person defined by the current Korean ventilation standard is not an effective policy for securing acceptable indoor air quality. Defining building component and people component ventilation rates separately and then
maintaining building component ventilation independent from the level of occupancy is the more efficient way of treating building generated contaminants.

Fig. 5. DCV with Modified Korean Ventilation Standard.
3.2.5. DCV impact on energy consumption

Fig. 7 shows the fan energy consumption during the day under CO₂-DCV and the simple binary control with the various ventilation standards. For simplicity, it is assumed that the DOAS system has a supply fan and a return fan, static pressure for each fan is set to 500 Pa, and fan efficiency is 65%. As expected, all CO₂-DCV cases consume less fan energy than the simple binary control case under the current Korean ventilation standard. CO₂-DCV with the ASHRAE Standard 62.1 consumes only 31% of fan energy with respect to the binary control case. The CO₂-DCV cases with original and modified Korean ventilation standards consume 45% and 54% of fan energy, respectively, with respect to the simple on–off control case. The DCV with modified Korean ventilation standard shows a little higher fan energy consumption than that of the DCV with original standard because of the building component ventilation maintained as background ventilation during the entire operating time. The RFID–DCV approach shows the same level of fan energy savings, so the detailed description is not included in this paper.

On the other hand, let’s assume that the DOAS system shown in Fig. 1 supplies ventilation air at a neutral temperature (i.e. the same temperature as room air temperature), the effectiveness of the enthalpy recovery device (e.g. enthalpy wheel) is identical in each DCV case, and hourly occupancy schedule, space cooling and heating loads are also shared together in all cases during the entire year. Given that, the differences in annual energy consumption for air conditioning among the cases will be caused only by the outdoor air conditioning load which is directly proportional to the outdoor air intake.
From this simple conjecture, one may conclude that the major factor of annual energy savings acquired by the DCV is the reduction of outdoor air intake.

4. Conclusions

In this study, two attractive DCV approaches, CO₂–DCV and RFID–DCV, were applied to DCV simulations for a theoretical public assembly space served by a dedicated outdoor air system (DOAS) with an enthalpy recovery device. By comparing DCV simulation results for the ASHRAE Standard 62.1-2007 and Korean ventilation standard, it was found that the current occupant based ventilation standard of Korea may provide unstable ventilation control especially in CO₂–DCV because of frequent and large scale changes of supply air amount.

As a solution to this problem, the current ventilation standard was modified by referring to the ASHRAE standard 62.1-2007, which shows good applicability to various DCV methods and applied to CO₂–DCV again. The result showed that the modified Korean ventilation standard stabilizes the ventilation system control and also provide acceptable indoor air quality. In the modified standard applied DCV, fan energy consumption increases insignificantly with respect to the original standard applied DCV case because of the building component ventilation delivered constantly during the operating time.

The DCV with accurate monitor of the real-time number of occupants such as RFID–DCV showed similar results to the CO₂–DCV case. However, in RFID–DCV, the ventilation system control was more stable and not very sensitive to types of ventilation standard applied.

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