A review of total volume environment and individually controlled micro-environment

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Abstract. Indoor environment has great effects on the health, comfort, and performance of occupants in modern buildings. The energy used for ventilating of buildings is substantial. However, ventilation based on total volume air distribution in spaces is not always an energy efficient way to provide high-quality indoor environments. Recently, individually controlled ventilation, which is designed to supply clean air where, when, and as much as needed, makes it possible to efficiently achieve high-quality indoor environment while reducing energy use. The personalized solutions generate a micro-environment that covers the space where the user spends a relatively long time. This review based on a number of experimental and numerical studies on total volume ventilation, zonal ventilation and personalized ventilation to assess the most suitable methods for indoor environment. Performance in terms of thermal comfort, air quality and energy efficiency are examined. In this study, different ventilation systems are classified according to specific requirements and assessment procedures. Finally, a discussion on the application and benefits of these ventilation is conducted and gives a direction for further investigation. The analysis results form a basic framework regarding the application of personalized ventilation in future.

1 Introduction

The traditional HVAC system aims to create uniform conditions in the entire conditioned space. It has been generally assumed that providing indoor environment preferred by an "average" person ensures the best thermal comfort 1. There is potentially, however, a controversy between the need to provide better indoor environment and to reduce energy consumption for buildings ventilation. The ideal solution for this situation could be to improve indoor environment with energy-efficient ventilation design.

Advanced ventilating methods and new solutions based on heat, contaminant, and air distribution control are urgently required. Today's centralized heating, ventilating, and air-conditioning (HVAC) systems must be replaced with decentralized room systems, personalized micro-environmental systems attached to furniture. Providing each occupant with active control over micro-environment is an important new principle that will make it possible to achieve much higher levels of indoor environmental quality. Therefore, research on implementation and operation of the individually controlled micro-environment in general, in buildings is important.

The European guidelines define three categories of indoor environment 2. It suggests that the highest quality of indoor environment, Category A, may require individual control of the micro-environment of each occupant in a space. ASHRAE standard 55 (2004) also suggests individually controlled under some conditions 3. In this case, personalized ventilation can be applied, which aims to condition only a relatively small space around the occupant in contrast to the traditional HVAC systems. Recently, different personalized conditioning systems have been introduced, including personalized ventilation 4, a combination of personalized ventilation with local convective and radiant heating 5, 6, a personal environmental module 7, or even a phase change material cooling vest 8. It has been shown that these systems improve an individual's comfort and reduce the energy consumption when designed and used properly 48.

2 Total volume ventilation

2.1 MV and DV

The mixing ventilation (MV) and displacement ventilation (DV) are two major total volume ventilation methods that have been widely studied.

The use of mixing ventilation has been well defined in various international standards regarding thermal comfort and indoor air quality 2, 9, 10. Recently, the design and application of MV was already systematically illustrated by Dirk Muller 10. The principle behind a MV system is to dilute the contaminated room air by mixing the

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supplied fresh air with indoor air to lower the contaminant concentrations, as shown in Fig.1 a).

DV is based on the principle of displacing contaminated room air with fresh air from outside, as shown in Fig. 1b) 12. The most common method to calculate airflow rates with DV is the temperature-based method. Cool air is normally supplied at low velocity (typically < 0.5 m/s) at or near the floor to create an upward air movement (thermal plumes) as it is warmed up by heat sources in the room. This will normally create vertical gradients of air velocity, temperature and contaminant concentration.

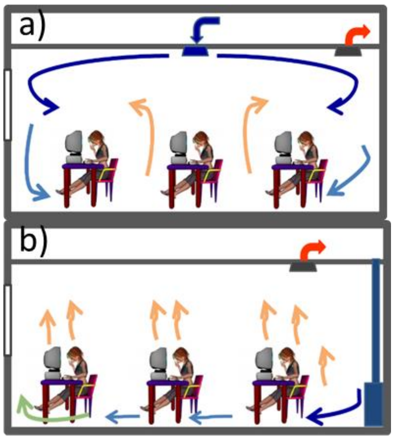

Fig. 1. a) mixing ventilation and b) displacement ventiation

Comparison with MV, DV can maintain a better IAQ, especially for breathing zone. The results show that the air is younger at breathing zone for DV than that of MV. And CO_2 generated by the occupants is also easier to be expelled in the DV cases. The workshop with high cooling load would require a high ventilation rate. For DV, high cooling load requires much higher air recirculation than that for conventional MV in order to maintain thermal comfort. In practice, it is not appropriate to apply DV for spaces with excessive cooling load 13. The air velocity of DV is smaller than 0.2 m/s. The temperature difference between the head and foot level of a sedentary occupant is less than 3 K. The percentage of dissatisfied people due to draft (PD) is 10% and the predicted percentage of dissatisfied is less than 20%. The result shows that besides being not energy-efficient and being not cost-efficient, a high ventilation rate might also have adverse effect on thermal comfort 14.

2.2 SV

Stratum ventilation (SV) supplies conditioned air horizontally to the breathing zone, forming a sandwich shape vertical air temperature profile with the lowest value at the head level, as shown in Fig. 2.

Because the supply air enters the breathing zone directly, the supply air path is shorten. Therefore, the mean age of air is younger, the ventilation effectiveness is higher and indoor air quality is better in the breathing zone. The particle concentrations for the entire room and for the breathing zone under stratum ventilation were less than that under displacement ventilation.

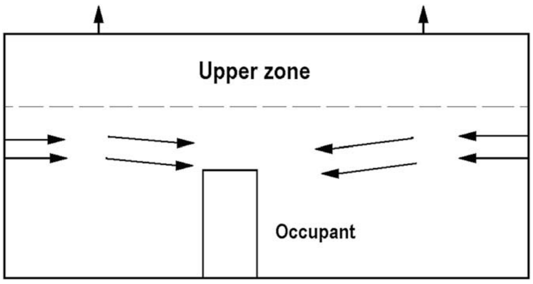

Fig. 2. Conceptual diagrams of stratum ventilation [19].

However, the deposited particle mass on room walls and furniture surfaces under stratum ventilation was bigger than that under displacement ventilation 15. Tian et al. found the inhaled air quality for the occupant improved when supply air temperature increased from 19 to 21 °C by numerical method and experimental test 16. He also showed that the ventilation effectiveness is close to 1.5. Hence, this ventilation method could therefore be expected to provide satisfactory indoor air quality in an energy-efficient way 17.

Fong et al. indicated that stratum ventilation could provide a satisfying level of thermal comfort even when the room temperature is up to 27°C using human test subjects 18. Computational results also show that stratum ventilation has the potential to maintain better thermal comfort with a smaller temperature difference between the head and foot level 15. Cheng et al. found air velocity and temperature in the occupied zone are reasonably uniform by adjusting room temperature, supply airflow rate and supply terminal type. The requirement of an air diffuser performance index (ADPI) of at least 80% was achieved for most cases. Subjective assessments using the ASHRAE 7-point scale indicate that thermal sensations of subjects in stratum ventilation are also uniform 19. It was found that the room temperature had a great impact on the overall thermal sensation, local thermal sensation and draft. Increasing the supply airflow rate from 7 ACH to 17 ACH, only exhibited a small influence on the thermal sensation and draft, indicating a preference for more air movement. More than 80% subjects felt comfortable under the neutral temperature of 27°C. However, to minimize draft complaints, the supply air temperature should not be below 20°C 20.

Lin et al. summarizes the year-round-totaled energy consumption for the various cases investigated without part-load control. The percentage primary energy saving is 44% with the use of stratum ventilation when compared with mixing ventilation. With a higher fresh air ratio like the classroom, the percentage energy saving can be even up to 74% for stratum ventilation 21. Lee et al. found that the year round energy saving was also substantial, typically around 20% and 40%, when compared with displacement ventilation and mixing ventilation, respectively 22.

3 Individually controlled micro-environment

The term "human micro-environment" was related to the environment in the vicinity of the human body 23, 24. The characteristics of the micro-environment depend on the interaction of its parts and on several factors, such as the uniformity of the surrounding environment, the posture of the body, its movement and contact with surfaces (e.g. furniture), clothing design, conditions at the skin, and the impact of external factors (air movement, thermal radiation, etc.). Therefore, the micro-environment is not uniformly distributed over the body and that it changes over time.
Melikov investigated the micro-environment around a human body, and especially on its interaction with the surrounding environment. The free convection flow generated by a human body (including the convective boundary layer around the body and the thermal plume above the body), its interaction with external invading flows and the resulting heat and mass transfer is included, all of which are important for thermal comfort and inhaled air quality 25. Experimental researches on air flow distribution close to human body, convective and radiative heat transfer from human body to the surrounding environment have been carried out 2630.

During the last few years, CFD technology has progressed and made it possible to analyze the micro-environment around human body. A growing number of computational thermal manikins have been proposed with the purpose of determining parameters that are not able, at least very difficult, to be obtained from experiment or making a comparison with experiment results 3134.

3.1 POV

The protected occupied zone ventilation (POV) was defined by using a low turbulent plane jet to separate an office environment into several subzones, as shown in Fig. 3 35. Hence, POV can be applied in a protected occupied zone.

Unlike traditional ventilation systems, which are based on total volume airflow method, the principle of POV is to separate an internal space into different personal work areas or subzones using downward plane jets. POV may be employed to reduce the exposure of people in a protected zone from indoor pollutants emitted in a source zone. The protecting effect of the POV system is attributable the disruption of the direct exhalation flow in the micro-environment around the two manikins. The local micro-environment created around the manikins with the downward plane jet was observed and no collision of the rising thermal plume and the plane jet was found 36.

The capacity of a POV system to separate the room into two zones with different concentration levels of contaminant indicates that the POV may protect people from infection of epidemic respiratory disease via a cross-contaminant inside a room. The findings have shown that a POV may reduce the risk of exposure to indoor gaseous pollutants emitted in the source zone 37-39.

It was found that the protection efficiency of the POV varies from 8% to 50% depending on the supply air velocity, the location of exhaust and the use of a partition 35.

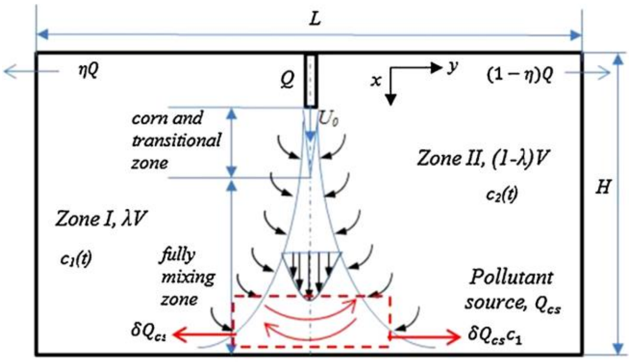

Fig. 3. Protected occupied zone ventilation [35].

3.2 PV

Personalized ventilation (PV) aims at supplying high-quality air directly to the exposure region, as shown in Fig. 4. During the last two decades, many studies have performed to improve the air quality of a person's working environment via personalized ventilation 40-51.

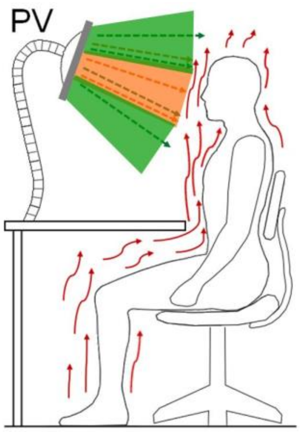

Fig. 4. Personalized ventilation.

The clean air supplied far from the occupants is more or less polluted and warm by the time it is inhaled with total volume ventilation. The improvements of air quality by personalized ventilation are well documented by a number of studies using a thermal manikin 51-57 as well as human subjects 51, 58-65. The highest quality of inhaled air can be achieved when the flow of clean and cool personalized air penetrates the free convection flow and reaches an occupant's face unmixed with the surrounding polluted room air. PV air supplied at a low turbulence level has resulted in better perceived air quality 47. Physical measurements identify a significant decrease of pollution concentration in inhaled air with PV in comparison with traditional ventilation 40, 66-74. The amount of inhaled clean personalized air has been shown to depend on the design of the ATD and its positioning in regard to the occupant. The flow rate (typically from less than 5 l/s up to 20 l/s) and the direction of the personalized airflow, as well as the difference between the room air and the PV airflow temperature, size of target area also influence 50, 55. By using PV, the percentage dissatisfied with air quality, 3 min after initial occupancy, decreased from 22% with MV to 7% with PV 58.

In rooms with mixing ventilation, the use of PV will always protect the occupants from airborne transmission of infectious agents and will be superior to mixing ventilation alone 69. Khalifa et al. investigated how to use PV to reduce the mixing processes by the personal ventilation jet 75. In rooms with displacement ventilation, however, PV promotes mixing of the exhaled air with room air 69, 73. A similar effect may occur in rooms with underfloor ventilation 71-73. Therefore, in order to keep an acceptable background environment, total volume ventilation in combination with PV can best be applied in rooms with high heat and/or pollution loads.

Substantial potential of PV for improvement of occupants' thermal comfort has been measured as well 43, 58, 75-80. The acceptability of the thermal environment with PV compared with without PV significantly improves at room temperature above 23°C. Control over supplied airflow rate, i.e., local air velocity, obviously makes it possible to avoid draught discomfort. It has been documented that PV improves occupants' thermal comfort, especially in warm environments [80, 81]. The thermal comfort level can also be improved by using PV. The Predicted Percentage of Dissatisfied (PPD) reduce from 27% (without personalized ventilation) to 16% (with personalized ventilation) 52.

A chair equipped with fans to enhance the convective plume has been investigated in conjunction with displacement ventilation by Sun et al. 82. Even a personalized cooling system incorporated in the clothing has been recently tested. A vest equipped with phase change material improved thermal comfort at rather extreme temperatures, which can occur in the office environment during summer heat waves 83. Faulkner et al. designed a task ventilation system with an air supply nozzle located underneath the front edge of a desk and measured air change effectiveness ranged from 1.4 to 2.7, which higher than conventional ventilation 84.

Table 1. Performance of different ventilation compared with mixing ventilation and typical applications

	Indoor air quality	**Thermal comfort**	**Energy benefit**	**Application**
DV	++	-	++	high ceiling height, high density of persons and lot of contaminants
SV	++	++	+	class room type of space
POV	++	-	-	places to protect spreading of contaminants
PV	+++	+++	+++	workplaces for personal control

The summary shows that up to 80% of inhaled air could consist of fresh personalized air with a supply flow rate of less than 3.0 l/s 85. In addition, it was shown that personalized ventilation can save up to 60% and 51% of energy compared with mixing ventilation in cold and hot climates, respectively 86, 87. Some studies shown the improvement in work performance and inhaled air quality by DV and PV, with saving of about 20% energy 40, 48.

Furthermore, PV combined with a passive chilled beam my save up to 80% of the ventilation air compared to mixing ventilation alone 87. PV used to supply clean out door air to each desk combined with a separate background mixing ventilation system that is used to condition and recirculate the room air has been shown to be a promising strategy that leads to improved indoor environmental quality at the desk and up to 50% energy saving compared to mixing ventilation alone 87.

4 Discussion and conclusion

As shown in Table 1, there are three indices that can be used to assess the performance of a ventilation system regarding indoor air quality, thermal comfort and energy efficiency. In addition, the performance of different ventilation systems will be determined by their specific tasks and such systems could also be assessed by different indices.

In practice, the individual differences, based on factors such as age, gender, clothing, activity, or body mass, make it impossible to satisfy the comfort need so fall the occupants using a total volume conditioning 88. Present total volume air distribution principles are inefficient because it does not account for individual differences between occupants and provides only limited or no personal control at all over their microenvironment. Thus, total-volume ventilation has limitations and is often unable to provide each occupant simultaneously with high level of thermal comfort and air quality.

Energy saving potential of using different ventilation methods should be evaluated by taking into account comprehensive conditions in the space, i.e. work performance, inhaled air quality, thermal comfort. The combination of different types of ventilation, like DV and MV, PV and DV, might have a better performance than using only one method.

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