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Influence of ventilation on energy consumption and carbon emissions in high occupant density building

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Abstract
Reasonable determination of outdoor airflow for building ventilation is very useful for indoor air quality improvement and building energy conservation. Variation characteristics of outdoor airflow requirement, building energy consumption and carbon emission for ventilation with indoor occupant density and ventilation time were analyzed for high occupant density building space, according to the indoor air pollutants mass-balance mechanism and outdoor airflow calculation principle in GB50019-2003 and ASHRAE Standard 62.1-2007. Advices for building energy conservation and reducing carbon emissions were given based on the variation characteristics for controlling indoor air pollution.

Keywords: Indoor air pollution, Outdoor airflow, Energy consumption, Carbon emissions.

1. Introduction

Indoor air pollution is one kind of low concentration pollution and concentrations of most indoor pollutants generally don't surpass the limit of related health standards [1, 2]. Without surpass doesn't mean indoor air has good quality and symptoms of sick building syndrome still occur commonly [3-8]. Ventilation is one of main methods to control the concentration level of indoor pollutants and improve indoor air quality, besides control of pollution sources and indoor air purification, and it's also one very effective and irreplaceable measure for controlling indoor low concentration air pollution [9, 10]. However, how much outdoor airflow is enough for this purpose is one critical problem, which affects improvement of indoor air quality, building energy consumption and even carbon emissions, especially for high occupant density building space, e.g. theatre, mall and library and so on. In order to choose reasonable outdoor airflow for indoor air environment improvement, the relationships among indoor occupant density, ventilation time, outdoor airflow requirement, energy consumption and carbon emissions were discussed in this study, which provide guides for building design and management.

2. Determination of outdoor airflow for ventilation

Indoor air pollution is the result of multiple factors interaction, including inadequate outdoor airflow, indoor sources, outside sources and others, the influence proportion of each factor can be seen in Figure 1. It can be seen from Figure 1 that adequate outdoor airflow is very essential for indoor air quality improvement.

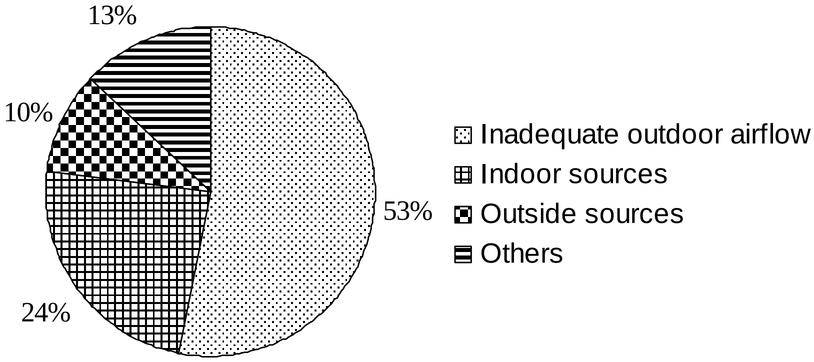

Figure 1. Reasons for indoor air pollution

However, how much outdoor airflow of ventilation is adequate for controlling indoor air pollution? In fact, the outdoor airflow requirement of building room depends on quantity of indoor air pollution sources and pollutants mass balance mechanism. The indoor air pollution sources include occupant-related sources, building-related sources and outside-related sources. The composition of each type source and its pollutants were given in Table 1 [11-14].

Table 1. Indoor air pollution sources and pollutants

Type	Sources	Pollutants
Occupant-related Sources	Human Breath Skin Metabolism	carbon dioxide ammonia sulfured hydrogen carbon monoxide volatile organic compounds
Building-related Sources	Building materials Paints/adhesives/solvent Furnishing Commercial products	formaldehyde volatile organic compounds radon ozone ammonia
Outside-related Sources	Motor vehicles Industry Public work Agriculture Ground Sewage	sulphur dioxide nitrogen Oxides carbon monoxide volatile organic compounds ozone lead particulates

The purpose of ventilation is keeping concentration of indoor air pollutants at allowed level. While there are five factors determining indoor pollutants concentration, including emission of indoor air pollution sources, dilution with outdoor airflow, air purification, chemical reaction and heterogeneous removal. Therefore, the indoor air pollutant concentration can be obtained in accordance with equation (1).

$$C=(C_0-\frac{G+C_iA_i-R}{A_i+KA_r+V_dS})e^{-(A_i+KA_r+V_dS)t/V}+\frac{G+C_iA_i-R}{A_i+KA_r+V_dS} \tag{1}$$

where C_0 is the indoor initial concentration of indoor air pollutant (mg/m^3), C_i is the air pollutant concentration of outdoor airflow (mg/m^3), G is the emission of indoor air pollution source (mg/s), A_i is the outdoor airflow (m^3/s), A_r is the circulation airflow of air purification (m^3/s), K is the purification efficiency, R is the indoor air pollutant remove caused by chemical reaction (mg/s), V_d is the deposition velocity (m/s), determined by the molecular diffusion coefficient, S is the area for heterogeneous removal (m^2), V is the volume of building room (m^3), t is the ventilation time (s).

If the air purification, chemical reaction and heterogeneous removal were ignored, the outdoor airflow can be gotten from equation (2).

$$C=(C_0-\frac{G+C_iA_i}{A_i})e^{-(A_i/V)t}+\frac{G+C_iA_i}{A_i} \quad (2)$$

In fact, it may take some time for C to reach the maximum indoor allowable pollutant concentration (C_n) when indoor initial pollutant concentration (C_0) is less than C_n. Therefore, the ventilation process can be divided into two stages, the C was assumed to equal to the average of C_0 and C_n in the first stage ($t<V/A_i$), and equal to C_n in the second stage ($t-V/A_i$). Of course, the steady ventilation state appeared when ventilation time was long enough.
In addition, China Ventilation Standards GB50019-2003 and ASHRAE Standard 62.1-2007 in USA also provide methods for determination of outdoor airflow at steady state, seen in equation (3) and (4) [10, 15].

$$A_i=A_pP \quad (3)$$

$$A_i=R_pP+R_aF \quad (4)$$

where A_p is the outdoor airflow rate required per person in GB50019-2003 ($m^3/(h\cdot person)$), P is the zone population, R_p is the outdoor airflow rate required per person in ASHRAE Standard 62.1-2007 ($m^3/(h\cdot person)$), R_a is the outdoor airflow rate required per unit area in ASHRAE Standard 62.1-2007 ($m^3/(h\cdot m^2)$), F is the zone floor area (m^2).

3. Variation characteristics

Due to difference of ventilation time and occupant retention time, there were three typical high occupant density building space, including theatre, mall and library, whose geometry sizes and outdoor airflow rates were given in Table 2 [10, 15].

Table 2. Geometry sizes and outdoor airflow rates

	Buildings types		
	Theatre	Mall	Library
Area [m^2]	2076.00	2435.00	1620.00
Height [m]	7.00	5.00	4.00
R_p [$m^3/(h\cdot person)$]	18.00	13.68	9.00
R_a [$m^3/(h\cdot m^2)$]	1.08	1.08	2.16
A_p [$m^3/(h\cdot person)$]	20.00	20.00	15.00

3.1 Outdoor airflow requirement variation

Indoor occupant density of high occupant density building space is variable obviously with time and behaves different characteristics in different region, which is affected by season, climate and holidays. Therefore, outdoor airflow for controlling indoor air pollution is changing with indoor occupant density and ventilation time, seen in Figure 2, 3 and 4. It can be seen that the outdoor airflow increased with ventilation time for theatre, mall and library, when C_0 was more than C_n, but it's reverse when C_0 was less than C_n, as a result of different ventilation efficiency. Of course, the outdoor airflow may remain unchanged after long enough ventilation time.
For another hand, when indoor occupant density raises, the outdoor airflows of theatre, mall and library also increased for any definite ventilation moment. Moreover, the outdoor airflow of theatre derived from equation (4) was more than that obtained from equation (2) in initial period, and the less the indoor occupant density was, the longer this situation lasted. But the outdoor airflows of mall and library gotten from equation (4) were less than those derived from equation (2) for any definite indoor occupant density and ventilation time, and this was also true for the relationship between outdoor airflows of library obtained from equation (2) and equation (3) respectively. In addition, there existed critical indoor

occupant density. The outdoor airflows of theatre and mall derived from equation (2) were more than those obtained from equation (3) when indoor occupant density was less than critical indoor occupant density, and vice versa.

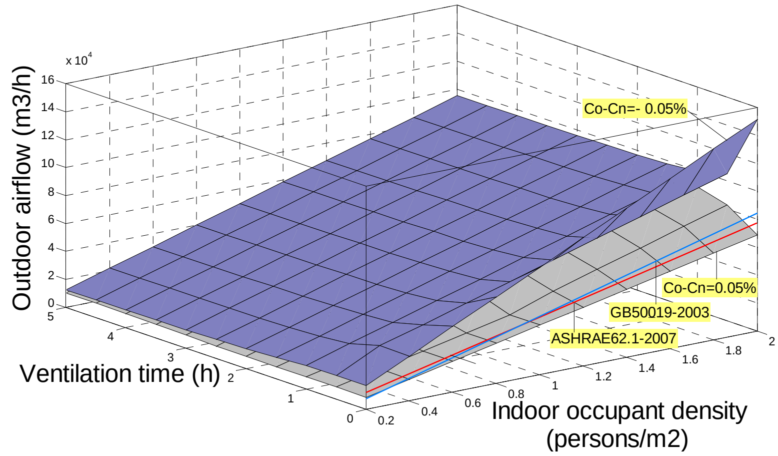

Figure 2. Outdoor airflow variation of theatre with indoor occupant density and ventilation time

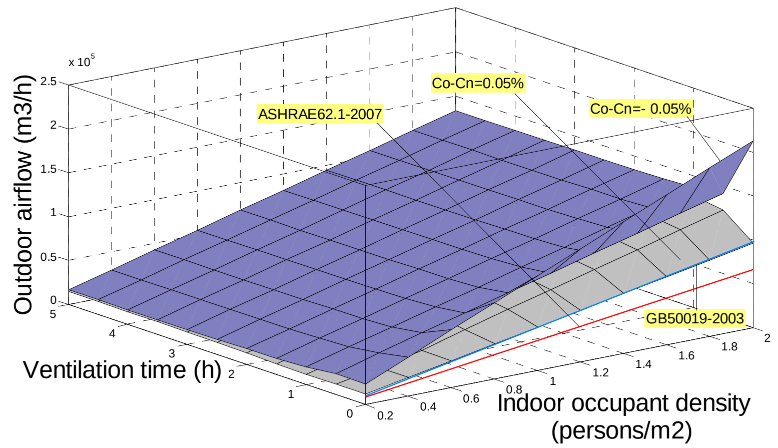

Figure 3. Outdoor airflow variation of mall with indoor occupant density and ventilation time

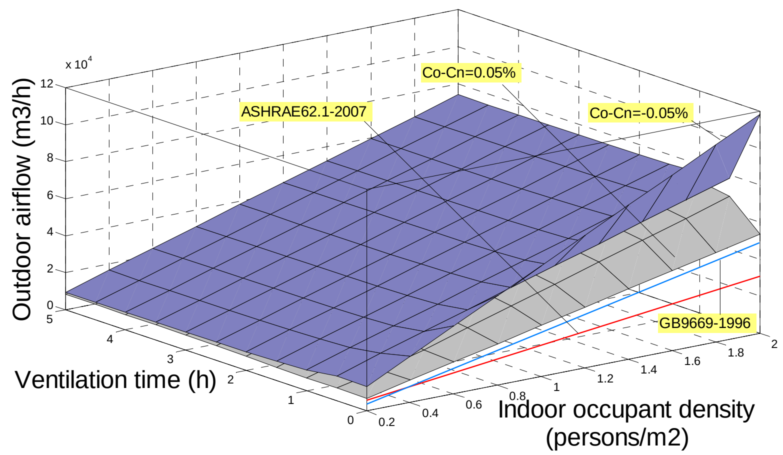

Figure 4. Outdoor airflow variation of library with indoor occupant density and ventilation time

Actually, when C_0 was less than C_n, it may allow without ventilation before C_0 reaches to C_n. The time of this process can be seen in Figure 5.

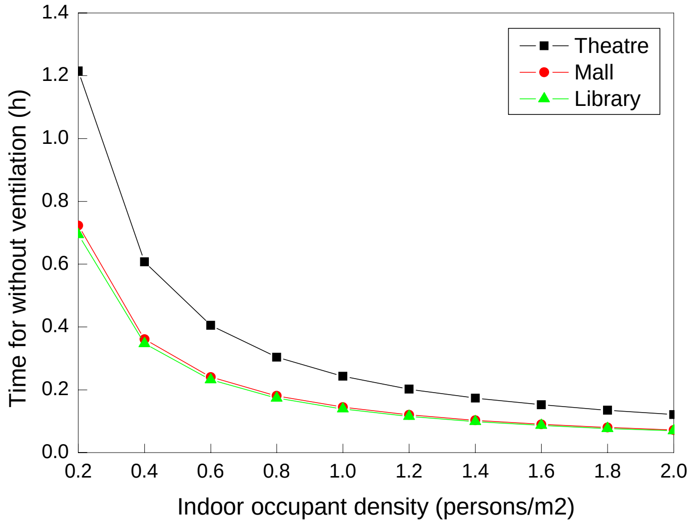

Figure 5. Time for without ventilation (C_n-C_0 =0.05%)

3.2 Energy consumption variation

Building energy consumption caused by outdoor airflow for building ventilation refers to treatment and transportation of outdoor airflow, the former includes refrigeration in summer, dehumidification in transition seasons, heating in winter. Energy consumption of one kilogram outdoor airflow can be obtained in accordance with equation (5).

$$q = q_{t1} + q_{t2} \qquad (5)$$

where q_{t1} is the energy consumption for treatment of outdoor airflow, q_{t2} is the energy consumption for transportation of outdoor airflow.

The building energy consumptions of theatre, mall and library for building ventilation in 5 hours in a typical day of summer were given in Figure 6. It can be seen that the building energy consumptions increased linearly with indoor occupant density. Moreover, the larger building area was, the higher growth rate of building energy consumption was for the same method to determine outdoor airflow. In addition, the difference between building energy consumptions obtained from mass balance relationship (MBR) and ASHRAE Standard 62.1-2007 (or GB50019-2003) respectively was very remarkable, but it's not for those derived from ASHRAE Standard 62.1-2007 and GB50019-2003. Therefore, it's very important to choose reasonable method to determine outdoor airflow of ventilation for building design and management.

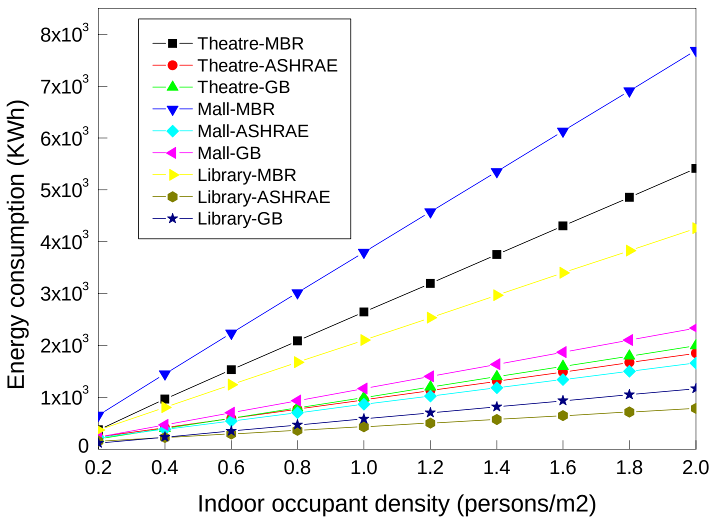

Figure 6. Energy consumption variations of theatre, mall and library for building ventilation

3.3 Carbon emission variation
Building carbon emission caused by outdoor airflow for building ventilation roots from fossil energy consumption. Carbon emission of building energy consumption can be derived from accordance with equation (6).

$$E_{CO_2} = q\varepsilon \quad (6)$$

where ε is the carbon emission coefficient of fossil energy consumption.
The building carbon emission of theatre, mall and library for building ventilation in 5 hours in a typical day of summer are given in Figure 7. The variation trend of carbon emission is similar to that of building energy consumption. It's worth pointing out that stopping ventilation before C_0 reaches to C_n and using green building materials are also useful for reducing building carbon emission, besides choosing reasonable outdoor airflow for building ventilation.

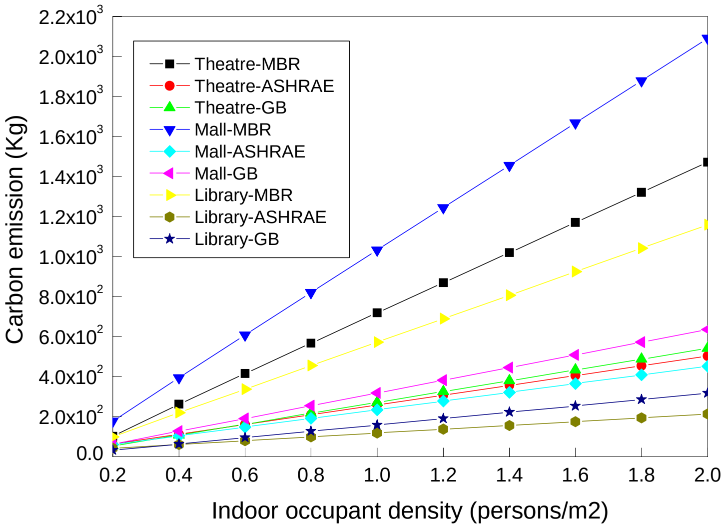

Figure 7. Carbon emission variations of theatre, mall and library for building ventilation

4. Conclusion
Outdoor airflow requirement variation with indoor occupant density and ventilation time for high occupant density building space given in this study is essential for choosing effective ventilation strategy and improving indoor air quality. Moreover, decrease of building energy consumption and carbon emission for ventilation depends on reasonable determination of outdoor airflow, which is also important for coordinating requirement of indoor air quality improvement and requirement of building energy conservation.

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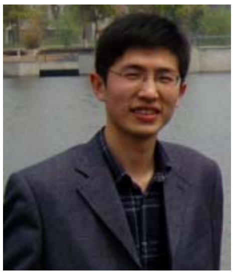

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