NUMERICAL SIMULATION ON TRANSIENT ACCESSIBILITY OF SUPPLY AIR AND CONTAMINANT SOURCE IN VENTILATED ROOM

Xiaojun Ma 1, Jiujiu Chen 2, Fenfei Zhu 1, Xiaoliang Shao 1, and Xianting Li 1*
1 Department of Building Science, School of Architecture, Tsinghua University, Beijing, China
2 Beijing Institute of Architectural Design, Beijng, China
*Corresponding email: xtingli@tsinghua.edu.cn

ABSTRACT

The transient accessibility of supply air (TASA) and transient accessibility of contaminant source (TACS) in ventilated rooms are important indices to evaluate the effect of ventilation and the indoor air quality (IAQ). These indices can be measured by experimental method or calculated with computational fluid dynamics (CFD) tools. Compared to the measurement method, the numerical method has a lot of advantages such as fast, flexible and with detailed data.

In this paper, the calculation and validation of the TASA and TACS are introduced. A typical ventilated room, which is 4m long, 3m wide and 2.5m high, is taken as the example to be calculated. The values of TASA and TACS in the room are obtained by numerical simulation with two kinds of ventilation modes. The two ventilation modes are, upper-wall-supply and lower-wall-exhaust, and, floor-supply and ceiling-exhaust, which are the typical mixing ventilation and underfloor ventilation.

By comparing the numerical results with the measurement data, the numerical method is validated. Furthermore, the two typical ventilation modes are evaluated by using the series indices of TASA and TACS obtained by the numerical method. It is shown that the indices are feasible of application.

KEYWORDS

Ventilation effectiveness, Transient accessibility, Computational fluid dynamics, Validation

INTRODUCTION

Contaminant dispersion in ventilated rooms will greatly influence indoor air quality, which is important for human comfort, health and safety (Sundell, 1996; Wargocki et al., 1999). The usual technique to predict the contaminant distribution in ventilated rooms is Computational fluid dynamics (CFD). Since the computation with CFD technique is always time-consuming, it is difficult to obtain so many cases that people can know how different kinds of factors impact quantitatively on the contaminant distribution.

In many cases, the air flow field can achieve steady state much faster than the dispersion of contaminant, and the contaminant can be treated as passive gas which has no influence on the airflow field. Thus, the evolution of contaminant distribution may be available without computing process of CFD technique.

New concepts, accessibility of supply air (ASA) and accessibility of contaminant source (ACS) were proposed to evaluate how the supplied air from each inlets and contaminant sources influence the contaminant concentration in any point (Li and Zhao,2004). Based on the concepts of ASA and ACS, proposed an analytic expression to describe the contaminants disperse process under steady flow field with uniform initial condition (Yang et al, 2004). And considering boundary condition and initial condition, a general expression on time-average concentration of contaminant distribution was summed up (Li and Chen, 2008). But the research on transient value of contaminant distribution with accessibility concepts is not reported up to now.

In this paper, the calculation and validation of transient accessibility of supply air (TASA), transient accessibility of contaminant source (TACS) and the analytic expression under two typical ventilation modes are introduced. The potential applications of the indices are discussed finally.

METHOD

The supplied air and indoor source both influence the concentration in a space. The concept of "transient accessibility", including the transient accessibility of supplied air and the transient accessibility of contaminant source, is introduced to describe the contribution of each inlet and contaminant source.

Definition of TASA and TACS

Assuming only the air from the n_S th supply inlet contains contaminant (or tracer gas) and no source is present in the room, the TASA to an arbitrary indoor point p from the n_S th inlet is then defined as:

$$a_{S,p}^{n_S}(\tau) = \frac{C_p(\tau)}{C^{n_S}} \quad (1)$$

Where $a_{S,p}^{n_S}(\tau)$ is transient accessibility of supply air from the n_S th inlet to point p at moment τ, $C_p(\tau)$ is contaminant concentration at point p at moment τ, C^{n_S} is contaminant concentration of supply air from the n_S th inlet, τ is time moment from moment τ =0. TASA quantifies how easily the air from a supply inlet is continuously delivered into an indoor location. It is a function of the flow characteristic and has nothing to do with contaminant type or source.

Similarly, supposing that the supplied air is clean and only the n_J th source exists in the room, the TACS to an arbitrary point p from the n_J th source is then defined as:

$$a_{C,p}^{n_J}(\tau) = \frac{C_p(\tau)}{C_E^{n_J}} \quad (2)$$

where $a_{C,p}^{n_J}(\tau)$ is transient accessibility of the n_J th source to point p at moment τ and $C_E^{n_J}$ is the exhausted concentration under steady-state condition and its value can be calculated as following:

$$C_E^{n_J} = \frac{J^{n_J}}{Q} \quad (3)$$

J^{n_J} is the emission rate from the n_J th contaminant source and Q is total airflow rate for the ventilated space. TACS quantifies how easily the contaminant is continuously diffused into an indoor location. It is a function of both the flow characteristic and the source location, having nothing to do with the emission rate or contaminant type. TASA and TACS can be easily calculated with CFD tools or tracer gas measurement.

Analytic Expression of Transient Contaminant Dispersion

In many cases, the airflow field could reach steady state within much shorter time compared to air element diffusion process. When the contaminant has no impact on airflow, the flow field can be treated as steady one. The accessibility of each factor could be then calculated and assembled.

With the concepts of TASA and TACS, the relationship between the contaminant concentration at any indoor point and the influencing factors can be established accordingly:

$$C_p(\tau) = C_0 + \sum_{n_S=1}^{N_S}\left[(C_S^{n_S} - C_0)\cdot a_{S,p}^{n_S}(\tau)\right] + \sum_{n_J=1}^{N_J}\left[\frac{J^{n_J}}{Q}\cdot a_{C,p}^{n_J}(\tau)\right] \quad (4)$$

where $C_p(\tau)$ is the transient concentration at moment τ and C_0 the concentration at moment τ =0.

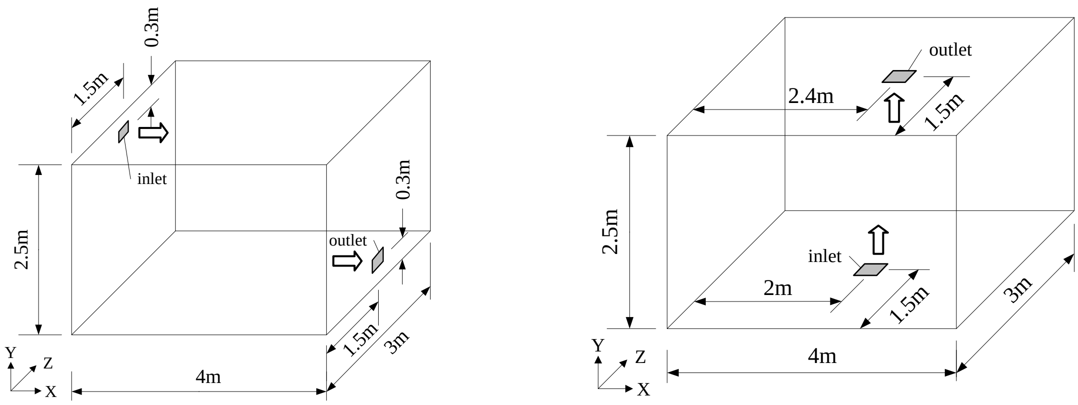
According to Eq. (4), the transient concentration distribution at any time, can be quickly calculated if the emission rate or the supplied concentration changes. Moreover, it shows the quantitative contribution of the factors that influence the indoor concentration.

CASE STUDY

Two cases with different ventilation modes were conducted. The series indices of TASA and TACS are illustrated. Furthermore, the two typical ventilation modes are evaluated by calculating the indoor contaminant distribution with TASA and TACS.

Case description

The demonstration room was shown in Fig. 1. The total air volume of inlet is $337.5m^3/h$.



(a) case 1 *(b) case 2*

Fig. 1. Sketch map of the cases

In each case, there are two schemes named SCHEME1 and SCHEME2 about the contaminant emission which their boundary conditions are illustrated as Table 1.

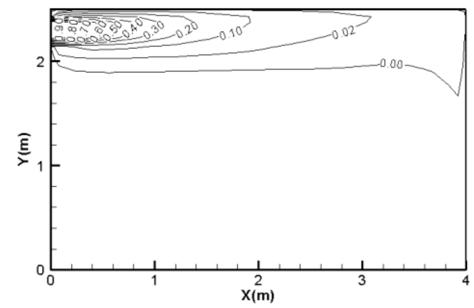
Table 1 The boundary conditions of two schemes

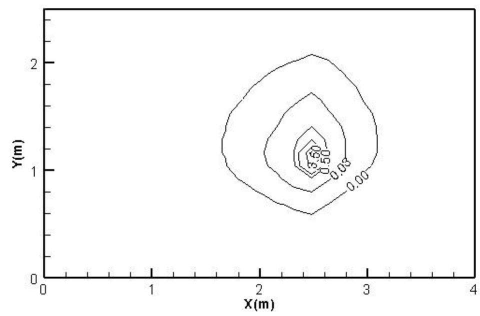
SCHEME 1		SCHEME 2	
Source from	Contaminant concentration (mg/m3)	Source location (mm×mm×mm)	Emission rate (mg/s)
Inlet	5	2.5(X) ×1(Y) ×1.5(Z)	0.47

A well-validated CFD program, STACH-3 (Zhao et al., 2003) is used as the simulation tool for TASA and TACS calculation.

Results and analyses

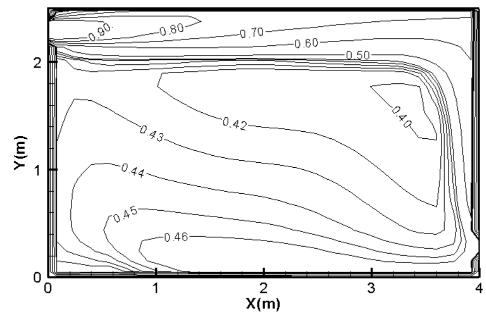
With the CFD tools, the TASA and TACS at different time of the two cases can be easily calculated as shown in Fig. 2 and Fig. 3. It reveals that airflow field dominates the TASA distribution in both cases, and the TACS is related to both the airflow field and source location.

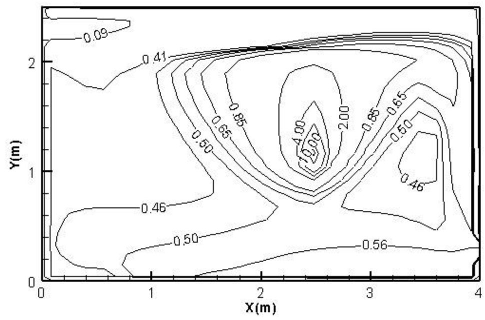




a) TASA at 10s

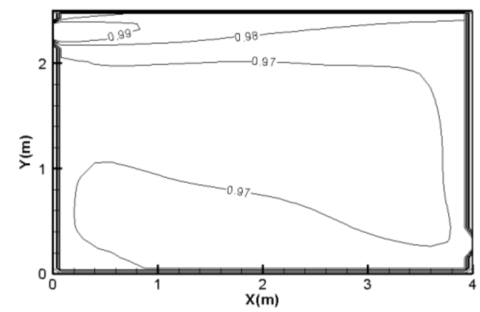
b) TACS at 10s

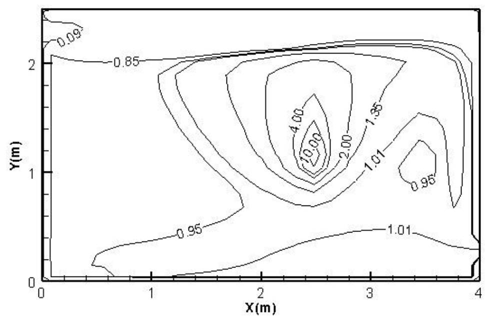




c) TASA at 300s

d) TACS at 300s

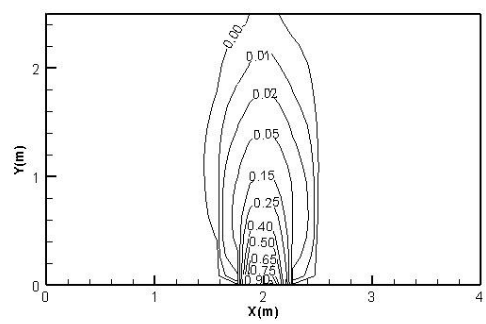


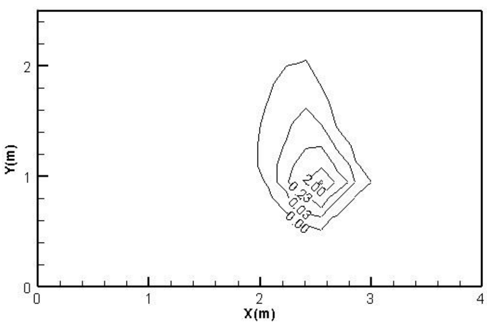


e) TASA at 1800s

f) TACS at 1800s

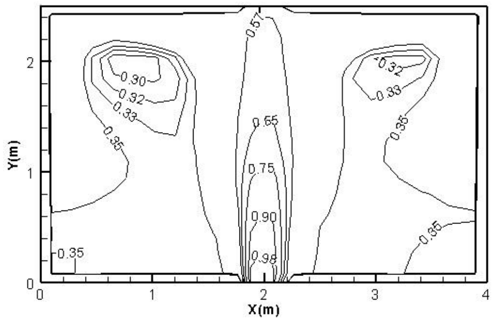
Fig. 2. TASA and TACS of case1 (section Z=1.5m)



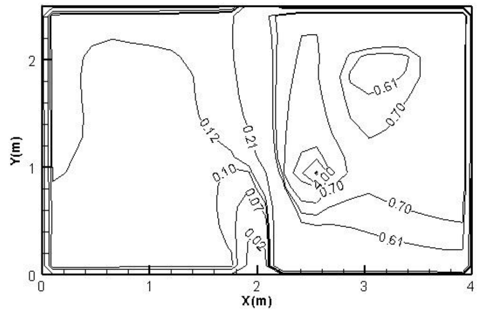


a) TASA at 10s

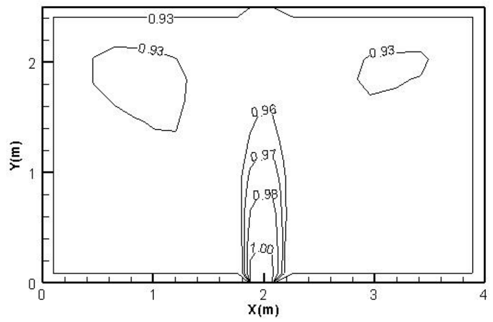
b) TACS at 10s



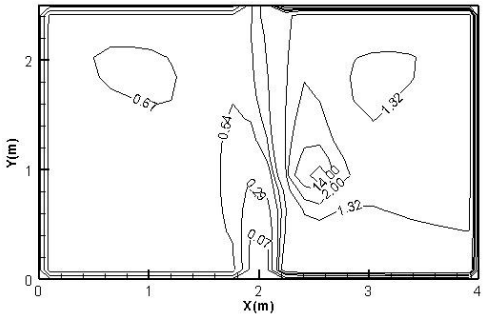
c) TASA at 300s



d) TACS at 300s



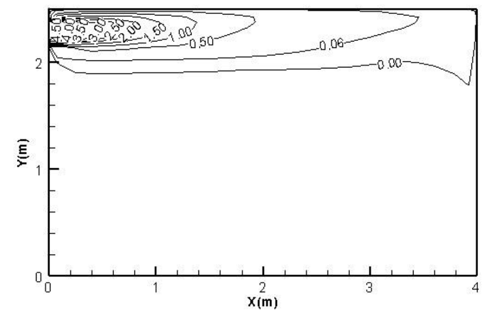
e) TASA at 1800s



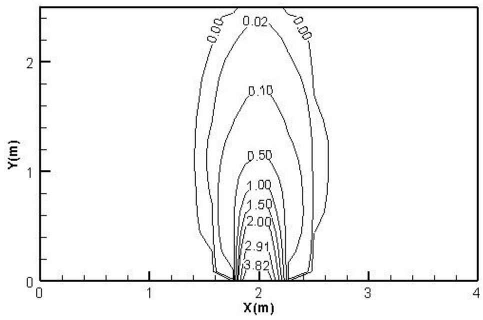
f) TACS at 1800s

Fig. 3. TASA and TACS of case2 (section Z=1.5m)

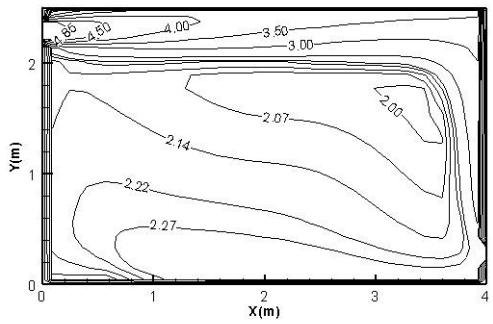
With the pre-calculated accessibilities, the contaminant distribution under different conditions can be easily calculated and compared by changing the corresponding parameters in Eq. (4). Fig. 4 and Fig. 5 display the development of transient concentration of different cases and schemes.



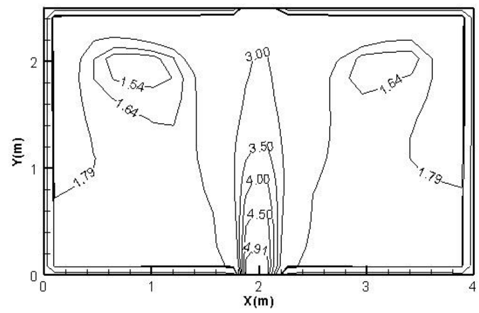
a) case1 at 10s



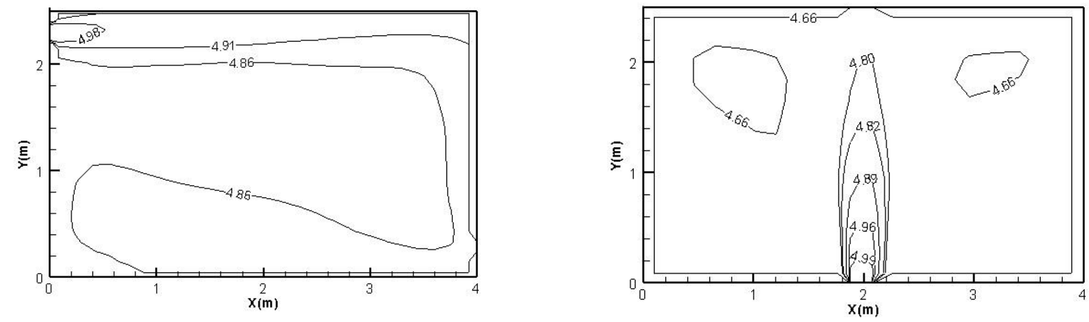
b) case2 at 10s



c) case1 at 300s



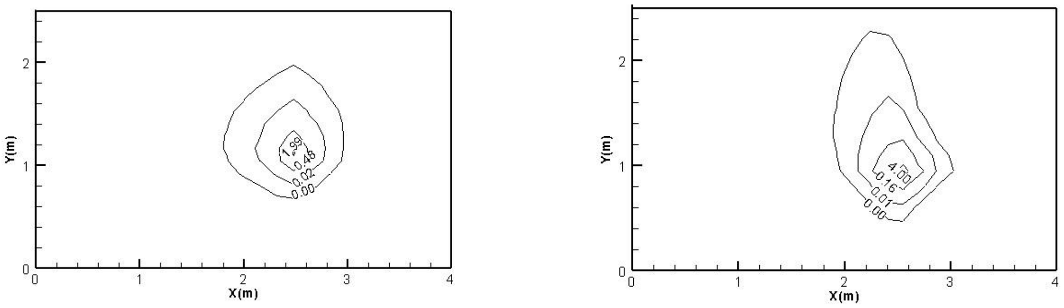
d) case2 at 300s



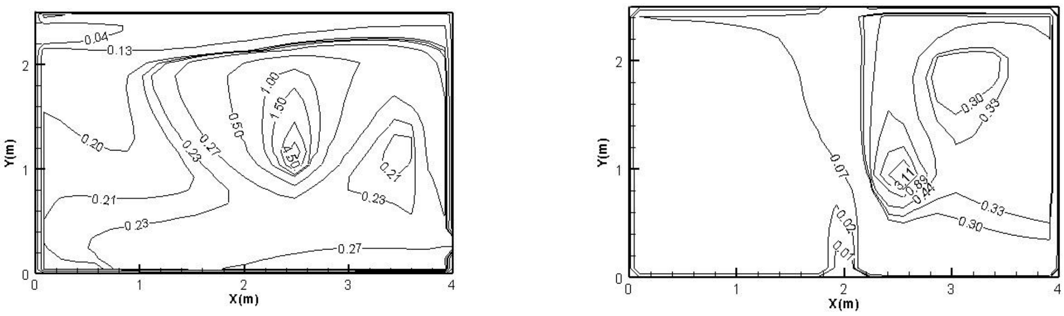
e) case1 at 1800s *f) case2 at 1800s*

Fig. 4. Contaminant distributions of SCHEME1 (mg/m3, section Z=1.5m)

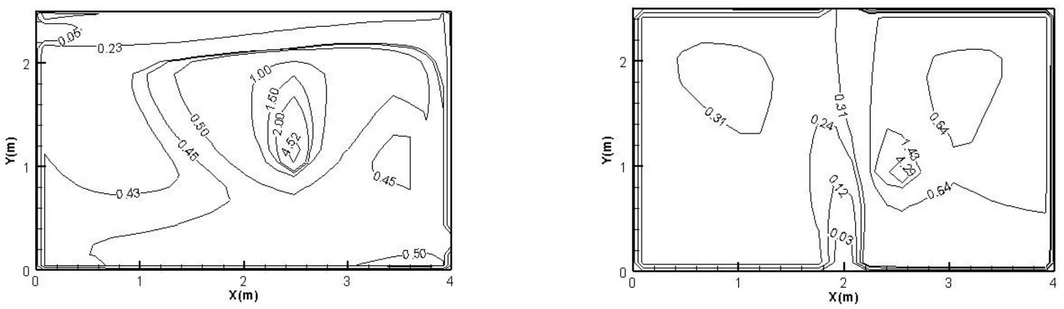
By comparing Fig. 4, it can be found that when the supply air contains contaminant, the concentration distribution in the room under different cases approached uniform with time. That means for these two cases, the influence of airflow is small.



a) case1 at 10s *b) case2 at 10s*



c) case1 at 300s *d) case2 at 300s*



e) case1 at 1800s *f) case2 at 1800s*

Fig. 5. Contaminant distributions of SCHEME2 (mg/m3, section Z=1.5m)

By comparing Fig. 5, it can be found that when there is a contaminant sources, the concentration distribution in the room under different cases differ greatly from each other. Which means the influence of the contaminant location is un-negligible.

VALIDATION WITH MEASUREMENT

In order to validate the results from Eq. (4), measurement in a climate chamber was conducted as shown in Fig. 6. CO_2 is chose as the tracer gas and emits in a steady rate from the start time in the supply air duct. The concentration of CO_2 in the inlet is controlled at 25 ppm during the emission. 6 CO_2 detectors are employed for this test. The no.6 detector, treated as the background concentration of the measurement, is put on outdoor that near the fresh air opening. The CO_2 concentration of each detector is recorded into the database of a computer for every one second. The CO_2 concentration is also calculated by using Eq. (3) with TASA which has been displayed before.

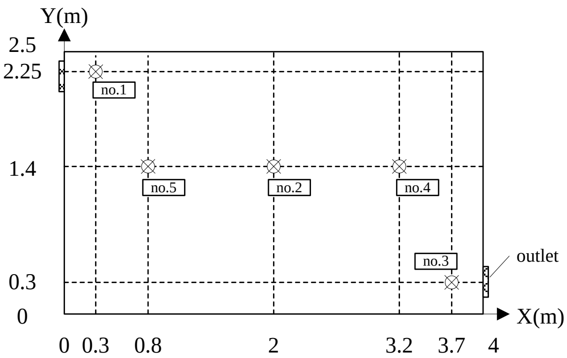


Fig. 6. Configuration of the test chamber

The Fig. 7 shows the relative error of every measurement point between the test data and the calculation results. Because there exist some inescapable recording error and delay of CO_2 detector, when the beginning of emission, that the changing of CO_2 concentration is acute, the error between test and calculation is higher, which the relative error is near to 100%. Through the changing of CO_2 concentration is slow with time passing, the relative error is drop obviously. When the process is near to stable, the relative error of no.2 to no.5 points are very limited, that the maximal value is not more that 12%. The error of no.1 point is about 25% since it close to the inlet, there might exist the undetectable unsteady air flow which can interfere the recording of detector.

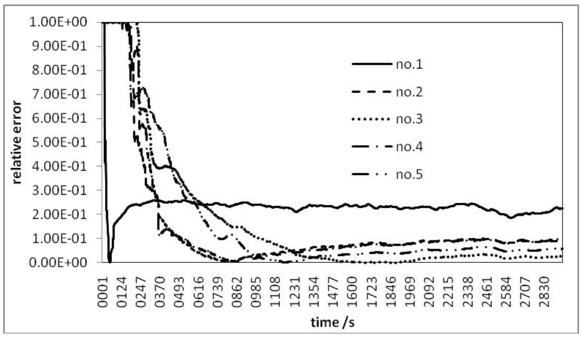


Fig.7 Relative error of CO_2 concentrations between test and calculation

By comparing the numerical results with the measurement data, it is concluded that the algebraic method to calculate transient contaminant concentration of this paper is creditable.

CONCLUSION

In this paper, the concepts of TASA and TACS are proposed to quantify the contribution of supply inlets and indoor sources on the transient contaminant dispersion in ventilated space. A quantitative relationship is built up based on these concepts to correlate transient distribution with related boundary conditions. The analytic expression is validated by tracer gas measurements. The application of the expression could greatly save both time and money, compared with the CFD simulation, thus the ventilation performance could be rapidly evaluated. The application of this method helps to choose the effective ventilation mode and to implement intelligent control to meet optimal requirements.

Furthermore, the wall boundary conditions and initial condition will also influence the contaminant distribution, which will be analyzed in the future work.

ACKNOWLEDGEMENT

This study is supported by The Eleventh Five-Year Plan key project of Department of Science of China (Grant No. 2006BAJ02A08), the National Natural Science Foundation of China (Grant No. 50578080) and the Program for NCET in University.

REFERENCES

Sundell, J., 1996. What we know, and don't know about sick building syndrome. ASHRAE Journal 38: 51-57.

Wargocki, P., Wyon, D.P., Baik, Y.K., Clausen, G. and Fanger, P. O., 1999. Perceived air quality, sick building syndrome (SBS) symptoms and productivity in an office with two different pollution loads. Indoor air 9: 165-179.

Li, X. and Zhao, B., 2004. Accessibility: a new concept to evaluate the ventilation performance in a finite period of time. Indoor and Built Environment 13: 287-293.

Yang, J., Li, X. and Zhao, B., 2004, Prediction of transient contaminant dispersion and ventilation performance using the concept of accessibility. Energy and Buildings 36: 293-299.

Li X., Chen J., 2008, Evolution of contaminant distribution at steady airflow field with an arbitrary initial condition in ventilated space. Atmospheric Environment 42: 6775-6784.

Zhao, B., Li, X. and Yan, Q., 2003. A simplified system for indoor airflow simulation, Building and Environment 38: 543-552.