Performance Improvement of an Operating Room in a Health-care Facility

Fu-Jen Wang[1*], Chi-Ming Lai[2], Zhuan-Ru Liu[1] , and Yuan-Hong Luo[1]

[1]*Department of Refrigeration, Air Conditioning and Energy Engineering, National Chin-Yi University of Technology, Taiwan.*
[2]*Department of Civil Engineering, National Cheng-Kung University, Taiwan.*

ABSTRACT

Not only operation rooms but also modern biochemical industries are increasingly turning to cleanroom technology for the infectious control or the development of new products. The objective of this study is to present the strategic approach on performance improvement for a hospital operation room under limited budget. The understanding of the key parameters contributing to performance of cleanroom can be developed by case study using computational fluid dynamics (CFD) aided simulation and then validated by field testing. Numerical simulation and field-testing of a full-scale operation room have been carried out in a district hospital in Taichung. A physical partition curtain has been conducted around the HEPA filter of an operation room to validate the improvement of air flow pattern. The results from computer simulation indicated that the improvement of airflow could be achieved by the optimal length of a physical partition curtain. Ventilation performance could be assessed extensively not only by calculation of ventilation indices but also by field test data of airborne particles counts and microbial counts.

Keywords: cleanroom, CFD, field testing, operating room

醫院手術室空調系統之性能改善分析

王輔仁[1*]　賴啟銘[2]　劉顓瑜[1]　羅元鴻[1]

[1]國立勤益科技大學冷凍空調與能源系
[2]國立成功大學土木工程學系

摘要

由無塵室所提供之潔淨環境條件對現代化生物科產業與健康醫療而言是極為重要的，本研究主要探討在有限經費預算時，如何針對醫院手術室之通風性能與污染控制提供評估改善策略。藉由計算流體力學(CFD)軟體進行全尺寸模擬真實位於台中之區域醫院手術室之氣流特性，並由現場量測粒子數及落菌數加以驗證模擬之結果。由電腦模擬結果得知，氣流的改善可利用建構於手術室送風口高效率濾網四周加裝阻隔風簾來達成，而通風效率及污染控制亦可由氣流場及濃度場分佈而得知明顯之改善。此外，空調通風系統之性能改善亦可透過通風指標計算及現場之微塵粒子及微生物落菌計數而加以驗證。

關鍵字：無塵室，計算流體力學，現場量測，手術室

文稿收件日期 97.10.01; 文稿修正後接受日期 98.07.17.; *通訊作者
Manuscript received October 1, 2008; revised July 17 , 2009. ; *Corresponding author

I. INTRODUCTION

The process of infection prevention for surgery often comprises complex procedures for different application. It is vital to control effectively the variables that interfere in the health and comfort of patients and surgical team. To achieve an acceptable performance, the operation room should realize a wide rang of control demands. Therefore, an explicit knowledge on contamination control and ventilation performance is essential to guarantee the ventilation system assuring health and comfort of occupants in the operation room.

A comprehensive review of the distribution patents and air movement in operation room has been presented in literature [1]. The importance of the airborne particles in the infection process and the efficiency of microbiological control for the main air distribution system have been analyzed and compared extensively. Their study also identified and demonstrated the control strategies which could reduce the risks of airborne contamination in operating infection. Furthermore, some research [2] investigated the airflow pattern and the diffusion of contaminants in an operating room with a diagonal air-distribution system using both experimental measurement and numerical modeling. The results revealed that the contaminant distribution depended strongly on the presence of obstacles such as personnel and medical apparatus.

Field-testing is to establish that the operation room performs correctly and achieves the contamination standards set down at the design stage. These standards related to cleanroom and associated environments are specified comprehensively in ISO 14644-1 [3]. The general principles and methods on bio-contamination control of cleanroom have been described extensively in ISO 14968 [4]. A lot of valuable information describing cleanroom tests to evaluate and characterize the overall performance of cleanroom and clean zone system can be found in IEST-RP-CC006.2 [5]. It also contains the latest data and information on cleanroom testing methods and procedures. Furthermore, NEBB [6] provides essential information on design consideration, requirements, techniques, equipments and comprehensive procedures for certified testing of cleanrooms. Besides, bioaerosol characteristics were evaluated in hospital cleanroom with different class levels [7]. It also indicated that bacteria levels were higher than fungal ones, which might be related to human dispersion.

Computational fluid dynamics (CFD) simulation technique is a scientific technique that allows improvement of cleanroom configuration without interfering with normal manufacturing processes [8]. The CFD codes were successfully used to simulate the air distribution and contamination decay in a model room as well as comparison of indoor particle concentration in different rooms [9]. Three-dimension air flow field for improving the ventilation performance of a minienvironment has been investigated in literature [10]. They found that the numerical and experimental approaches led to useful information and the ventilation performance in the minienvironment might be improved enormously by adjusting the location of the HEPA filter. Zhang [11] investigated the biological contaminant control strategies under different ventilation models in hospital operation room by using CFD simulation. Numerous parameters intended to characterized air flow pattern have been proposed. The concept of age-of-air [12], which was derived from temporal mixing theory, has been widely adopted to evaluate the ventilation performance. Furthermore, Federspiel [13] presented the development of methods for calculating relative air change effectiveness based on age-of-air measurement. Besides, the influence of a thermal boundary conditions on the air change efficiency of a mechanical ventilation system has been studied extensively [14].

In this study, field tests of a operation room have carried out in a district hospital in Taichung. The CFD simulation technique was applied to survey airflow characteristics based on field-testing data. A physical partition curtain has been conducted around the HEPA of the operation room to validate the performance improvement of air flow pattern and contamination control. Furthermore, the index of age-of-air was conducted to evaluate the ventilation performance under different length of partition curtain. All of the CFD simulation results will be compared and analyzed with field test data of airborne particles counts as well as microbial counts.

II. SYSTEM DESCRIPTION AND FIELD TESTS

The purpose of the ventilation system in an operation room is not only to achieve thermal comfort but also to remove airborne contamination. It is necessary to perform surgery in particle-free environment, minimization contamination and infection prevention. The layout of operation room in a district hospital in Taiwan is shown in Fig. 1. This facility with cleanliness level class 10000 (ISO class 7) is equipped with 6 high efficiency particulate air (HEPA) filters, ensuring air free from particles above 0.5 μm (99.97%). The measured cleanroom with the dimension of length(L)×width(W)×height(H) ＝ 5.5m×4.3m×3.0m. Return air grilles are included at the corner of operation room. The specified design condition are temperature 22±2 (℃), humidity 55±5 (%RH) and pressurization 10Pa.

The operating room encountered high particle counts and microbial counts in specific sampling location during field tests. Improvement of system performance has to be conducted through CFD simulation and field measurement. To provide reliable measurement data as the boundary conditions of CFD simulation, the temperature and face velocity of the HEPA filters have been tested with an ALNOR Model 8585 thermal (hot-wired) anemometer. Field-tests including the particle counts at specified sampling location were carried out. The 13 sampling points are also sketched in Fig. 1. Quantities measurement of airborne particle counts were made with a Met-One Model 3313 particle counter, sensitive to particles 0.3 μm, 0.5 μm or larger. Three times of measuring at each sampling location were conducted for accuracy and repeatability. To verify the numerical results on concentration of contaminations and ventilation performance, microbial counts have been measured as well with a Merck MAS-100 impaction sampler. The active sampling methods impact the microbe-carrying particles onto an agar surface. Bacteria were incubated for 48 hours at 30℃ in an incubator. Then, colonies are counted and hence the number of colony forming unit (CFU) can be ascertained.

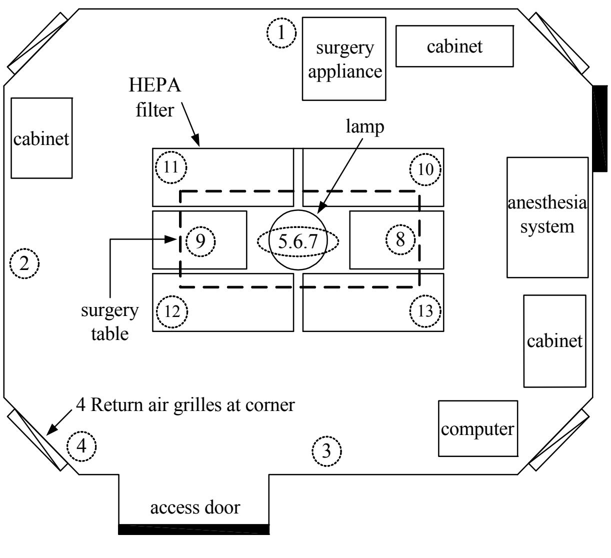


Fig. 1. Layout of the investigated operation room.

III. NUMERICAL SIMULATION

Due to the high particle counts from field testing at particular sampling locations, it revealed that improvement for airflow movement as well as contamination control was necessary for the operation room. Some airflow improvement strategies with a physical partition curtain were proposed and analyzed by numerical simulation. A commercial CFD code, STAR-CD [15], was used to simulate the airflow of operation room accordingly. It will examine the improvement of operation room configuration without interfering with normal processes in the surgery room.

The governing equations solved by STAR-CD include the three-dimensional time-dependent incompressible continuity, Navier-Stokes equation diffusion equation and k-ε turbulence equations. They are the continuity equation and the Reynolds-averaged Navier-Stokes equations expressed as

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_j u_i-\tau_{ij}\right)=-\frac{\partial p}{\partial x_i}+s_i \tag{2}$$

where x is the coordinate, subscripts i and j are the index of Cartesian component, u_i is the fluid velocity component in the i axis, ρ is the mass density, τ_{ij} is the stress tensor, p is the static pressure and s_i is the momentum source. These formulated equations can be found in the STAR-CD user's manual [15] as well as any CFD text books and will not be repeated here.

In the present study, the main process area of operation room was built to operate at cleanliness level higher than class 10000 (ISO class 7) and the full-scale geometric model along with personnel, surgery table and medical apparatus of operation room is shown in Fig. 2. It was assumed that the air flow field is homogenous, isotropic and three-dimensional. For the k-ε turbulence equation, the empirical turbulence coefficients were assigned as: σ_k=1.0, σ_ε=1.22, $\sigma_{\varepsilon1}$=1.44, $\sigma_{\varepsilon2}$=1.92, and Cμ=0.09 respectively. These values were widely accepted in CFD k-ε model. The well-known finite control volume method with a Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) algorithm was adopted to solve all the governing equations simultaneously. After the flow field was obtained, the unsteady state CO2 concentration field was calculated based on the following mass concentration equation and can be expressed as

$$\rho\frac{\partial C_m}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j C_m+F_{m,j}\right)=0 \tag{3}$$

where subscript m is the species, C_m is the mass fraction of the species, $F_{m,j}$ is the diffusion flux component.

Numerical simulation accuracy depends on the resolution of the computational mesh and a finer grid leads to more accurate solutions. The comparison of grid test for 1,000,400 cells and 700,950 cells possesses the relative error at 0.048 % with 1,000 timestep on the convergence criteria of 10^{-4}. In this study, a grid setup with approximately 700,950 cells was used for numerical simulation. The increase of cell number will provide more favorable information; however, it will accompany by a significant increase of computation resources. The boundary conditions of the solution domain have been clearly defined according to the actual field tests data to carry out the accurate solutions. Consequently, the face velocities of HEPA filter were steadily maintained at 0.3 m/s and the uniformity of the velocity distribution has been confirmed as well. Typically, the no-slip condition was applied on the solid walls and physical partition curtain around HEPA filter since they were not permeable. According to the airflow improvement strategies proposed, the numerical simulation of different curtain length (L) were conducted and assessed extensively.

The concept of age-of-air based on numerical concentration field has been incorporated to assess the ventilation performance of the operation room. Local mean age-of-air was calculated using the theoretical method by Sandberg [12]. It can be defined as the average time taken for air to travel from the inlet to any point in the room. Local mean age-of-air is expressed as

$$\overline{\tau_p} = \frac{\int_0^\infty C(\tau)d\tau}{C(0)} \qquad (4)$$

where $C(0)$ is the initial uniform concentration of the room, $C(\tau)$ is the concentration allowed to decay by replacement with air from HAPA filter at time τ. Therefore, the time $\overline{\tau_p}$ represents the time necessary to clean any point in the operation room. Another index for ventilation performance can be derived as the room mean age-of-air $\overline{\tau}_m$. It can also be directly calculated from

$$\overline{\tau}_m = \frac{\int_0^\infty \tau C_e(\tau)d\tau}{\int_0^\infty C_e(\tau)d\tau} \qquad (5)$$

where $C_e(\tau)$ is the total amount of concentration which leaves the room at time τ. The parameter $\overline{\tau}_m$ can be displayed as the mean time necessary to reach the total decontamination of the operation room.

Calculation of mean age-of-air gives the time elapsed since a measured volume of inside air has come from outside and it can be used to characterize the airflow pattern and ventilation performance. Transient simulation for concentration field at arbitrary point is essential for calculation the age-of-air. The concentration-decay simulation was adopted by assuming the initial contamination concentration of CO_2 at 2000 ppm in the operation room. All the calculation based on numerical simulation will be compared and analyzed with field test data of particle counts as well as microbial counts.

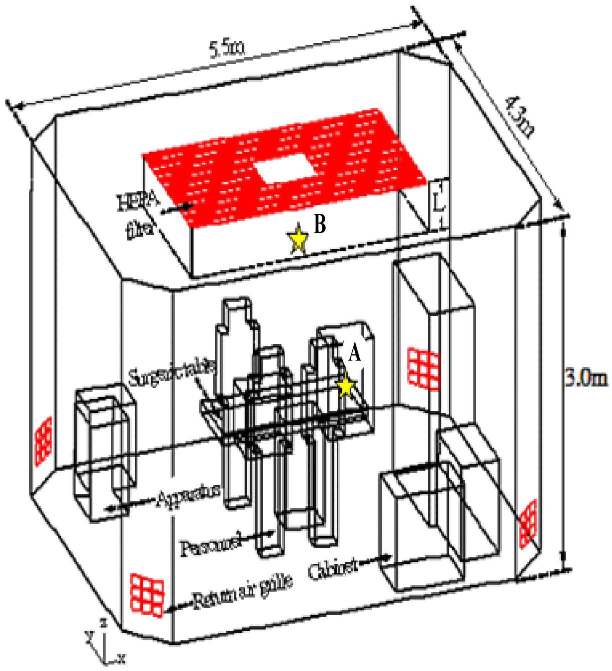
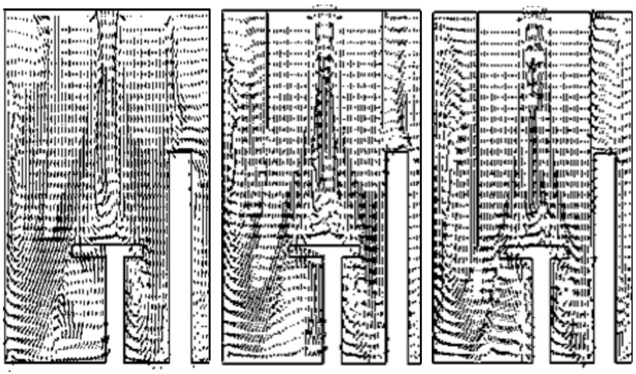


Fig. 2. Geometric model of the operation room.

IV. RESULTS AND DISCUSSION

The full-scale steady simulation for different curtain length of velocity vectors at cross section of y = 2.2 m are displayed in Fig. 3. As shown in Fig. 3(a), the case of length L=0m, which corresponds the base case without physical partition curtain, presents obvious vortex velocity vector above the surgery table. Another small vortex vectors are also inspected under the surgery table and around the corner of HEPA filters. The vortex velocity vectors can be reduced apparently by adding the partition curtain at length of 1.0 m, as shown in Fig. 3(b), which could provide satisfactory air flow pattern to achieve uni-directional flow. As presented in Fig. 3 (c) the case of L = 2 m depicts similar improvement with case (b), however, it might impose a considerable restriction on the surgical team and positioning of medical instruments as well.

As it is shown in Fig. 4., the concentration profile for different curtain length was simulated under time variation. It reveals that the contamination level above the operation bed can be reduced obviously by adding of physical curtain. The trend of concentration profile also corresponds by the velocity vectors shown in Fig. 3, although there exists minor cross contamination by mixing with the air outside the coverage area of HEPA filter in case (a) and case (b).



(a) L = 0.0 m (b) L = 1.0 m (c) L = 2.0 m

Fig. 3. Velocity vectors for different curtain length (at y = 2.2 m).

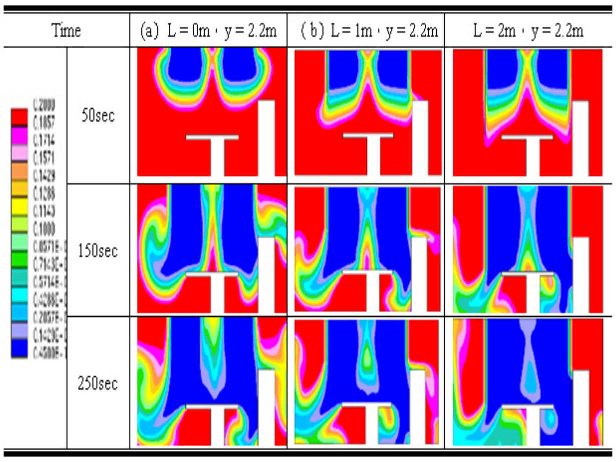
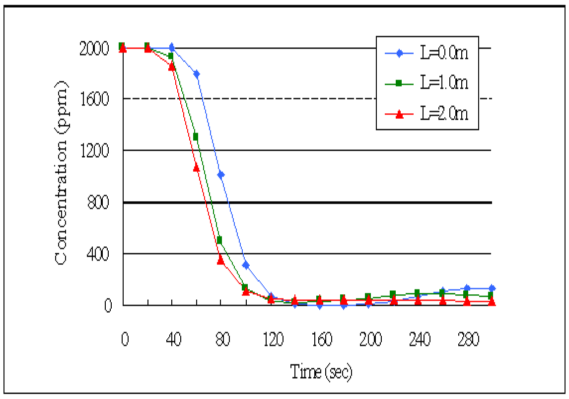
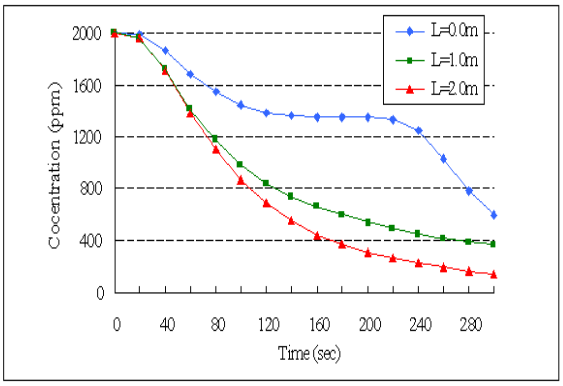


Fig. 4. Concentration field for different curtain length (at y = 2.2 m).

To investigate the effect of concentration field under different curtain length, two monitoring points specified with star sign were selected in Fig. 2 to survey the concentration decay rate above the surgery table (point A) and at center under the lamp (point B). Fig. 5(a) depicts the transient simulation of concentration decay rate at specified monitoring point A. It revels that the concentration decreases fasters when the curtain length L increases. It also demonstrates little time needed to reach a certain limit of concentration level, which represents better ventilation performance. For the case at point B, as shown in Fig. 5(b), the similar trend is found with increasing of curtain length. However, the concentration decay curve becomes flatter due to worse ventilation performance under the lamp. In the case without curtain (L = 0 m), the curve turn into horizontal because of induction mixing occurred. It also reveals that contamination control and ventilation performance will become worse to handle. Furthermore, the calculation of concentration decay after 300 seconds, room mean age-of-air and local mean age-of-air are shown in Table1. The local mean age-of-air reduced obviously by adding of partition curtain at both point A and point B. The mean age-of-air of the operating room exhibits the same trend with the local mean age-of-air. It also indicated that the ventilation performance can be improved by the adding of partition curtain.



(a) Monitoring point A

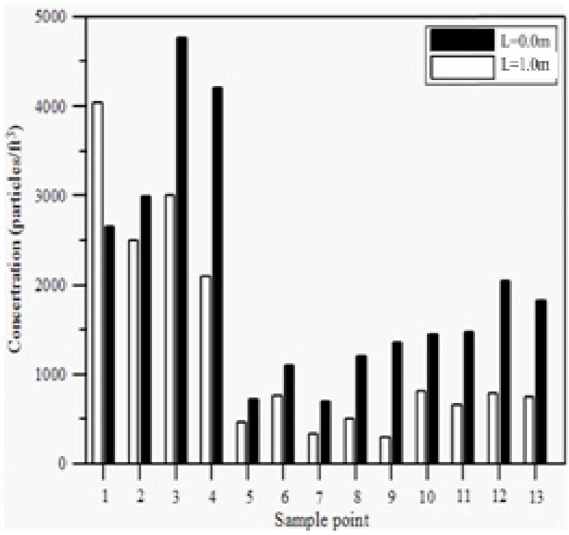


(b) Monitoring point B

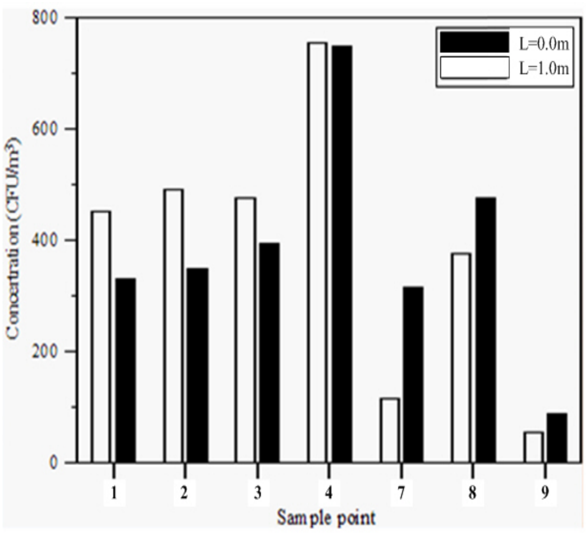
Fig. 5. Concentration decay curve under different curtain length at specified monitoring point.

The field measurement has been conducted according to the proposed strategy by using the anti-static plastic PVC curtain around the HEPA filters. To validate the numerical simulation results, the particle counts (≧ 0.5 μm) at different sample locations (shown in Fig. 1.) were measured and displayed in Fig. 6(a). Higher particle counts occur in the vicinity outside the surgery table area such as the region near wall and the corner regions of return air grille (sample point 3 and point 4). However, there still exists a high particle count at point 12 and point 13, which corresponds with the previous simulation flow pattern shown in Fig. 3. It is quite obvious to find that the particle counts reduce apparently by adding partition curtain. Most of the sample location could achieve the higher ISO 6 (class 1000) cleanliness level in the vicinity of surgery table.

Fig. 6(b) represents the field test data of microbial counts with and without partition curtain. The sampling point 7, 8, 9 were evenly displayed at the top, center and bottom of the surgery table respectively. The using of partition curtain reduces the microbial counts in the region of surgery table. It also corresponds with the numerical simulation of ventilation performance of the operation room. However, the microbial counts increase in the vicinity outside the surgery table such as sampler point 1-4. There still exists some inconformity tendency between numerical simulation and field measurement on microbial counts. Nevertheless, the concept of mean age-of-air and concentration decay curve could be used as useful index to predict the ventilation performance acceptably.



(a) Particle counts



(b) Microbial counts

Fig. 6. Field tests data of particle counts and microbial counts at specified sampling point.

Table.1. Calculation of concentration decay and age-of-air

Curtain length (m)	Monitoring points	CO_2 concentration decay after 300 sec (ppm)	Local mean age-of-air (sec)	Room mean age-of-air (sec)
L=0.0	A	132	43	423
	B	603	227	
L=1.0	A	68	22	417
	B	840	106	
L=2.0	A	32	19	383
	B	145	91	

V. CONCLUSIONS

This study investigated the field tests and airflow improvement by numerical simulation of an operation room in a health-care facility. The field tests have been carried out comprehensively using many delicate instruments. The airflow improvement strategy with a physical partition curtain could be assessed and identified through the technique of CFD simulation and the mean age-of-air calculation. Improvement of contamination control was accessible with less expenditure by adding the proper length of partition curtain. Results in this study could provide valuable information to the facility engineer facing the high particle counts and microbial counts in the operation room for infection control. It also revealed to identify the best practice under limited budget as well as to reduce the trial-and-effort while modification have to be carried out.

ACKNOWLEDGMENT

The authors would like to express their great appreciation to the financial support by the National Science Council under the grant No. NSC-96-2623-7-167-001-ET.

REFERENCES

[1] Pereira M. L. and Tribess A., “A review of air distribution patterns in surgery rooms under infection control focus,” Thermal Engineering, Vol. 4, pp. 113-121, 2005.

[2] Woloszyn M., Virgona J. and Melen S., “Diagonal air-distribution system for operating rooms:experiment and modeling,” Building and Environment, Vol. 39, pp. 1171-1178, 2004.

[3] ISO 14644-1. Cleanrooms and Associated

Controlled Environments - Part 1： Classification of Air Cleanliness, International Organization for Standardization, New York, USA, 1999.

[4] ISO 14698-1. Cleanrooms and associated controlled nvironments-Biocontamination control-Part 1: General principles and methods, International Organization for Standardization, New York, USA, 2003.

[5] IEST-RP-CC006.2, Testing Cleanrooms, Institute of Environmental Sciences, Illinois, USA, 1993.

[6] NEBB, Procedural Standards for Certified Testing of Cleanrooms, 2nd edition, National Environmental Balancing Bureau, Maryland, USA, 1996.

[7] Li, C. S. and Hou, P. A., “Bioaerosol Characteristics in Hospital Clean Rooms,” The Science of the Total Environment, Vol. 305, pp. 169-176, 2003.

[8] Manning, A. “Airflow modeling in cleanroom design,” Cleanroom, Vol. 19, pp. 22-25, 2005.

[9] Zhao B. and Zhang Y., “Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method,” Building and Environment, Vol. 39, pp. 1-8, 2004.

[10] Rouaud O. and Havet M., “Influence of external perturbations on a minienvironment: Experimental investigations,” Building and Environment, Vol. 39, pp. 863-872, 2004.

[11] Zhang R., Tu G. B. and Ling J., “Study on biological contaminant control strategies under different ventilation models in hospital operating room,” Building and Environment, Vol. 43, pp. 793-803, 2008.

[12] Sandberg M. and Sjoberg M., “The Use of Moments for Assessing Air Quality Ventilated,” Building and Environment, Vol. 18, pp. 181-197, 1983.

[13] Federspiel, C. C. “Air-change Effectiveness: Theory and Calculation Methods,” Indoor Air, Vol. 9, pp. 47-56, 1999.

[14] Tommso R. M. DI and Nino E., “Influence of the boundary thermal conditions on the air change efficiency indexes,” Indoor Air, Vol. 9, pp. 63-69, 1999.

[15] CD Adapco Group, Methodology STAR-CD, Version 3.15, Computational Dynamics Limited Corporation, 2001.