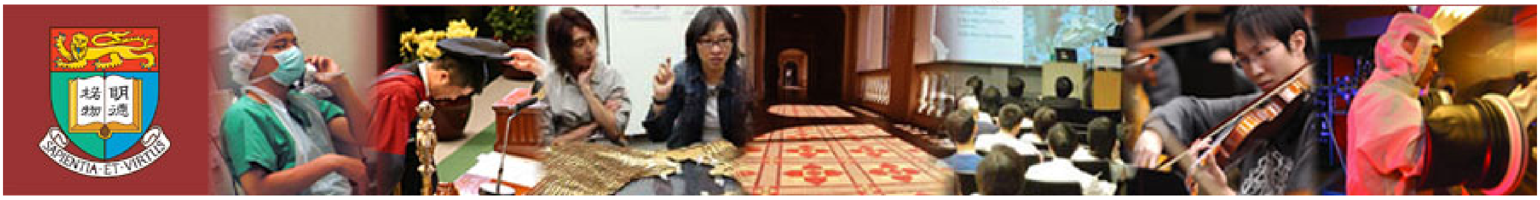

Title	**Numerical study of pollutant dilution in a natural ventilated dental clinic: ventilation path types used for exhausting pollutant**
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Citation	**The 2012 International Conference on Biomedical Engineering and Biotechnology (iCBEB 2012), Macau, China, 28-30 May 2012. In Conference Proceedings, 2012, p. 1572-1575**
Issued Date	**2012**
URL	**http://hdl.handle.net/10722/209437**
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2012 International Conference on Biomedical Engineering and Biotechnology

Numerical study of pollutant dilution in a natural ventilated dental clinic

Ventilation path types used for exhausting pollutant

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Abstract—**A dental clinic was modelled in this study using a Computational Fluid Dynamics (CFD) platform. The objective was to study the effect of natural ventilation on pollutant dispersion in this setting. Three basic ventilation paths were identified, the "single narrow path", "narrow path" and "dispersive path". The results show that the first of these had the highest efficiency, with an escape time of about 1/30 and 1/100 of the narrow and dispersive paths, respectively. Despite the position of the pollutant source and facilities such as bulkheads, escape time was significantly reduced when the ventilation flow rate was increased under the single narrow and dispersive paths. However, for the narrow path, these factors played a more dominant role in the escape time than the ventilation flow rate.**

Keywords-natural ventilation, wind paths, pollutant, residual time

I. INTRODUCTION

In hospitals and health care facilities, increasing interest has been focused on indoor air quality, because of the mixture of pollutants which may be present. Some attempts have been made to assess the indoor air quality of ventilated dental clinics. Pankhurst and Coulter review the evidence that dental unit waterlines are a source of occupational and healthcare-acquired infection in dental surgeries [1]. The microbial water, air and surface contaminations were studied during working and nonworking hours. Environmental pollution before and after dental procedures is also evaluated by Cellini [2]. The results show that the use of effective control procedures, and in particular an air filtration system, can be helpful in reducing airborne environmental contamination. Furthermore, Smith and colleagues [3] study the room layout and ventilation performance for pollutant concentration using primary data collected using a survey methodology.

Natural ventilation is often proposed in health care settings in order to control infection. It has a higher efficiency and lower energy consumption compared with mechanical ventilation systems. Furthermore, Building-Related Illness (BRI), Sick Building Syndrome (SBS) and Legionnaires' Disease are all typically caused by air conditioning systems. Seppanen and Fisk [4] show that the prevalence of SBS in buildings using air conditioning systems is between 30% and 200% higher than those which employ natural ventilation. Deaths caused by Legionnaires' disease have even occurred in direct evaporative cooling systems [5]. The outbreak of Severe Acute Respiratory Syndrome (SARS) took place in 2003. These indoor environment problems relating to the use of air conditioning systems have all taken place in buildings which use them for ventilation. In order to avoid such problems, reduce energy consumption and improve ventilation efficiency, the use of natural ventilation in residential buildings has been promoted by the Hong Kong government. As a sustainable method, it could also be used in dental clinics in Hong Kong due to their air intake status.

In naturally-ventilated buildings, pollutant control is always decided by ventilation performance. Karava and colleagues [6] examine the airflow of cross ventilation in a single-zone building using a wind tunnel experiment. The results show that it is difficult to predict the airflow pattern using an experimental method. Furthermore, the parameters, including inlet-to-outlet ratio and the positions of the openings in the façade wall, should be considered in the design of natural ventilation. Qian and colleagues [7] report on a field measurement exercise in a hospital. They conclude that when all doors and windows are open, a high ventilation rate can be achieved. Such previous work demonstrates the high efficiency of natural ventilation and the importance of having sufficient openings in reducing the level of pollution caused by hazardous substances. Generally, however, this can be influenced much more significantly by the ventilation operation schemes [8, 9] used in a naturally-ventilated room.

Accordingly, the objective of this study was to study the effect of natural ventilation on pollutant dispersion in a dental clinic. The Computational Fluid Dynamics (CFD) method was applied. The more accurate turbulence model, Large Eddy

978-0-7695-4706-0/12 $26.00 © 2012 IEEE
DOI 10.1109/iCBEB.2012.286

Simulation (LES) was used to study the flow field after validation with open experimental data. Discrete Phase Modelling (DPM) was then applied to study the pollutant dispersion. A simulation was conducted to study the ventilation paths and pollutant dispersion of various ventilation flow rates.

II. METHODOLOGY

A. *Air flow modelling using LES*

CFD is a commonly-used method of studying the natural ventilation performance and the particle dispersion outside and inside a building [10, 11, 12]. The accuracy of the simulation is decided by the choice of the turbulence model and meshing case.

In the LES model, turbulent flows are characterized by eddies with a wide range of length and timescale. The largest eddies are typically comparable in size to the characteristic length of the mean flow. The smallest are responsible for the dissipation of turbulent kinetic energy. For all flows, CFD code FLUENT solves the conservation equations for mass, momentum and energy. In LES, the three conservation equations can be solved directly in large eddies, while the smaller eddies are modelled. Large eddies are dictated by the geometry and boundary conditions of the problem to be resolved. Small eddies are less dependent on geometry, tend to be more isotropic and are consequently more universal.

The governing equations for LES are obtained by filtering the time-dependent Navier-Stokes equations in either Fourier (wave-number) or configuration (physical) space. The filtering process effectively filters out those eddies whose scales are smaller than the filter width or grid spacing used in the computations. The resulting equations thus govern the dynamics of large eddies.

A filtered variable (denoted by an overbar) is defined by equation 1:

$$\overline{\phi}(x) = \int_D \phi(x')G(x,x')dx' \tag{1}$$

where;

D —— the fluid domain,

G —— the filter function that determines the scale of the resolved eddies.

In FLUENT, the finite-volume discretization itself implicitly provides the filtering operation:

$$\overline{\phi}(x) = \frac{1}{V}\int_v \phi(x')dx',\ x' \in v \tag{2}$$

where;

V —— the volume of a computational cell.

The filter function, G (x, x'), which is implied here, is then:

$$G(x,x') = \begin{cases} 1/V,\ x' \in \upsilon \\ 0,\ x' \in \text{otherwise} \end{cases} \tag{3}$$

In this study, the LES model was used to solve the incompressible flows. By filtering the Navier-Stokes equations, one obtains:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \overline{u}_i) = 0 \tag{4}$$

and

$$\frac{\partial}{\partial t}(\rho \overline{u}_i) + \frac{\partial}{\partial x_j}(\rho \overline{u}_i \overline{u}_j) = \frac{\partial}{\partial x_j}(\mu \frac{\partial \sigma_{ij}}{\partial x_j}) - \frac{\partial \overline{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{5}$$

where σ_{ij} is the stress tensor due to molecular viscosity defined by:

$$\sigma_{ij} \equiv [\mu(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i})] - \frac{2}{3}\mu \frac{\partial \overline{u}_l}{\partial x_l}\delta_{ij} \tag{6}$$

and τ_{ij} is the subgrid-scale stress defined by:

$$\tau_{ij} \equiv \rho \overline{u_i u_j} - \rho \overline{u}_i \overline{u}_j \tag{7}$$

B. *DPM*

In FLUENT, DPM model follows the Euler-Lagrange approach. The fluid phase is treated as a continuum by solving the time-averaged Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles through the calculated flow field.

The trajectory of the particle in the second phase can be predicted by integrating the force balance on the particle in FLUENT, and the dispersion of particles due to turbulence in the fluid phase can be predicted using the stochastic tracking model. The integration of the force on the particle is described as equation 8:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x \tag{8}$$

where;

u — the fluid phase velocity,

u_p — the particle velocity,

ρ — the fluid density,

ρ_p — the density of the particle,

F_x — an additional acceleration (force/unit particle mass) term,

$F_D(u - u_p)$ — the drag force per unit particle mass. FD is defined in equation 9 as follows:

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D \mathrm{Re}}{24} \tag{9}$$

where;

μ — the molecular viscosity of the fluid,

d_p — the particle diameter.

Re is the relative Reynolds number, which is defined as:

$$\mathrm{Re} \equiv \frac{\rho d_p |u_p - u|}{\mu} \tag{10}$$

C. *3 Ventilation path types in a 2-dimensional (2D) simulation*

The dental clinic model used in the simulation was based on the study of Stathopoulou and colleagues [8]. There were six windows on one wall, and three doors on the opposite wall. In this clinic, the dental chairs were also spaced using the partition walls shown in Figure 1. Two staff rooms were placed on one side.

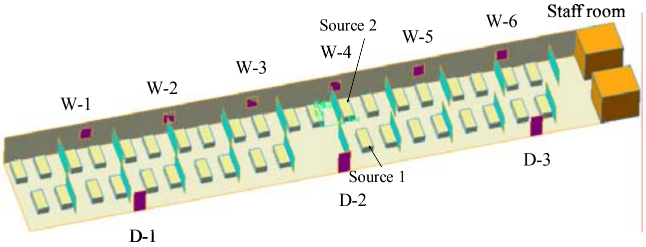


Figure 1 The layout of the dental clinic

In order to investigate the typical ventilation paths, the dental clinic was simplified into a 2D model with three doors and six windows on opposite sides as shown in Figure 2. Facilities such as bulkheads and staff rooms were ignored.

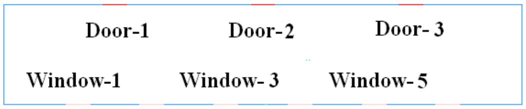


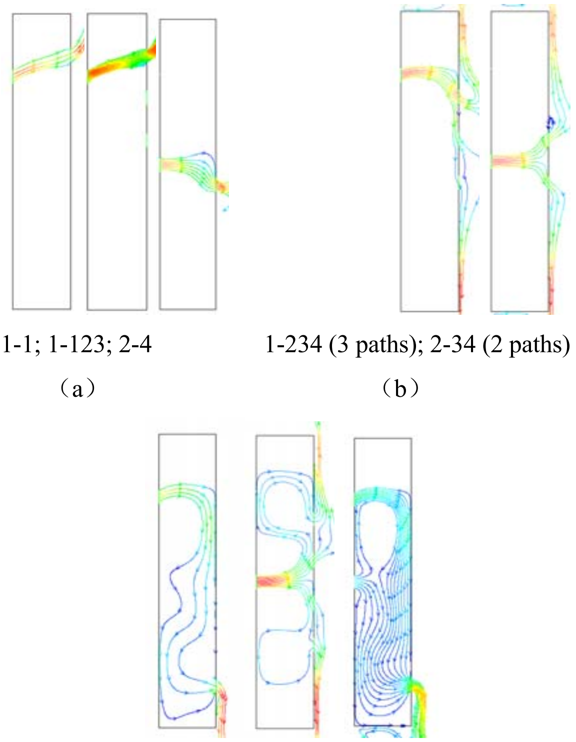
Figure 2 The simplified 2D simulation model

Three basic types of ventilation paths were obtained from the results of all the combination cases according to the dispersion conditions. Examples are shown in Figure 3.

Type 1 was summed up using 7 cases from the total of 57. It can be called the "single narrow path", and its route is basically the same as the distance from the inlet to the outlet. In the dental clinic setting, the dispersive area of type 1 was the smallest, so it had the minimum spread potential.

Type 2 can be called the "narrow path". It was summed using 5 of the 57 cases, but includes several ventilation routes. In this type, the number of ventilation paths equals the larger value between the inlets and outlets. The dispersive area is almost the smallest, but is still larger than type 1. Generally, in this situation, it will be easy to remain clear of pollution from hazardous substances so long as the particle tracks can be avoided.

Type 3 is the "dispersive path" summed up from 45 of the 57 total cases. In practice, this type is common but easily enables cross contamination. This condition always occurs when the outlet is far from the inlet or the wind coming from different inlets mixes together. The natural wind passes through almost the whole room. In this situation, the pollutants (especially those where deposition was difficult) were carried by the wind. The escape time of the pollutants from the office was much longer than those of the other types, and their spread area was also larger.



1-1; 1-123; 2-4

（a）

1-234 (3 paths); 2-34 (2 paths)

（b）

1-6; 2-2345; 12-6

（c）

Figure 3 Examples of three types of natural ventilation paths: (a) type 1: single narrow path; (b) type 2: narrow path; (c) type 3: dispersive path

III. APPLICATIONS

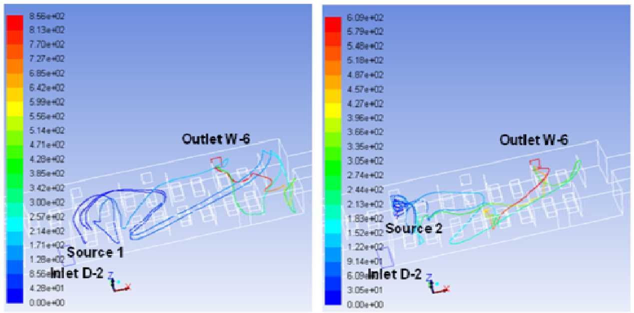
Three cases related to different ventilation path types were studied in this work, each including two different positions for the particle source. Source 1 was set to be a stable position on the dental chair near window outlet opening W-4, and Source 2 was near the door inlet opening D-2. The positions of the particle sources are also shown in Figure 1. Experimental data from the research of Stathopoulou and colleagues [8] were used as the boundary conditions, so the initial velocity inlet was set to be 1m/s.

In the dental clinic model, the total number of elements was 800,000. The grids were almost of the structured type, except for the narrow aisle. The focused results were the general flow field and the particle tracks, so the refined elements were not used in the near wall region.

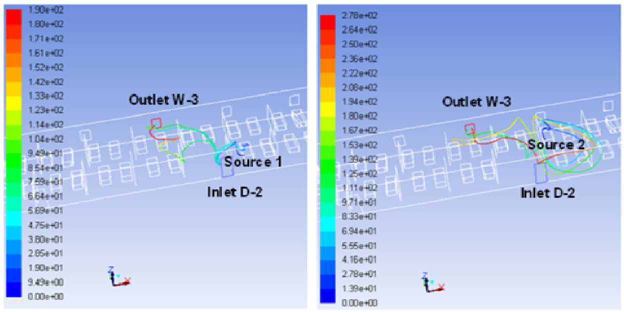
Each of three simulation cases, Case 1, Case 2 and Case 3, belonged to ventilation path type 1, 2 and 3, respectively. In Case 1, D-2 and W-4 were chosen as the inlet and outlet openings; in Case 2, these were D-2 and W-3 and in case 3, D-2 and W-6 were chosen. In all cases, the other doors and windows in the dental clinic were closed.

In each of these three cases, there were two conditions with different source positions (Source 1 and Source 2). Figure 5 shows the particle tracks in the clinic. In Figure 5 (a) for Case

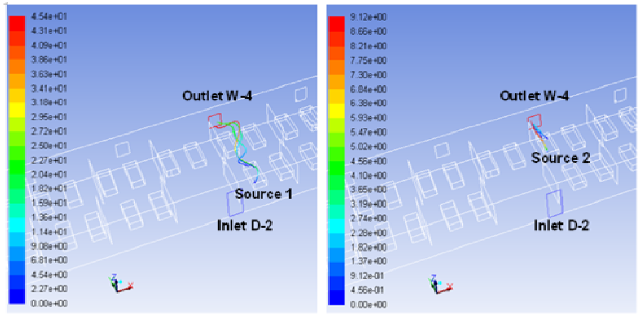
1, the escape time of one bundle of particles from Source 2 was much less than that of Source 1 because of the shorter escape path. The escape times from Sources 2 and 1 were 9.12s and 45.4s, respectively. A longer escape time means that the pollutant particle may have more influence on patients and staff located close to the source. In Figure 5 (b) for Case 2, the escape times from Sources 1 and 2 were 190s and 278s respectively. It can be seen from Figure 5 (c) for Case 3 that the area of pollutant spread from Source 1 was larger than that from Source 2. However, the potential for infection from Source 2 was greater due to the higher concentration of the pollutant, as shown in Figure 5 (c). The escape times from Sources 1 and 2 were 856s and 609s, respectively. In all three cases with two situations (two source positions), the longest escape time was almost 100 times the shortest.



(c) Case 3 (D-2 W-6)



(b) Case 2 (D-2 W-3)



(a) Case 1 (D-2 W-4)

Figure 5 The particle tracks of the two different positions of particle sources (Source 1 and Source 2) for three cases at the room inlet velocity of 1 m/s.

IV. CONCLUSION

This work has investigated the effect of natural ventilation on pollutant dispersion in a dental clinic. It examined the positions and ventilation path types of the clinic. The advanced turbulent model LES was used to simulate the flow field and DPM to evaluate the particle dispersion. From the analysis of particle tracks in the Source 1 condition, the escape time of the particles under the single narrow ventilation type was almost 1/100 of that under the dispersive type, and 1/30 of that under the narrow path type.

ACKNOWLEDGMENT

This work was supported by an International Competitive Research Grant (CRG) from the Hong Kong Polytechnic University (Project Account No. G-YH97).

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