Assessment of the ventilation in long-term care institutions in computational fluid dynamics

Yi-Wen Tu¹*, Chia-Ti Tseng¹, Jia-Kun Chen¹, Tsu-I Tseng²

¹ Institute of Occupational Medicine and Industrial Hygiene, National Taiwan University
² National Center for High-performance Computing, National Applied Research Laboratories

* r07841013@ntu.edu.tw

Abstract. Taiwan has entered aged society, the elderly are more and more dependent on long-term care institutions. Furthermore, the subjects for long-term care institutions in Taiwan are the elderly population and disabilities who are susceptible to the effects of indoor air quality. If people stay in the space with such poor indoor air quality, they may get sick building syndrome (SBS), allergy, and other respiratory diseases. The poor ventilation could make the disease worse and increase the probability of disease outbreaks.

The purpose of this study is to investigate to the benefit to control the indoor air quality in a room and to give a solution to indoor air quality (IAQ). On the other hand, we used software called computational fluid dynamics (CFD) to simulate a suitable ventilation strategy. We aim at investigating the performance of decrease carbon dioxide (CO2) concentration and other indoor air quality indicators and making an approach to the correlation between indoor air quality and flow movement.

1. Introduction

In the past researches, people spend around 90 percent of their time indoors, including work, rest, sleep, etc. [1]. Therefore, we pay close attention to the topic of the indoor air quality. Based on the house sampling, we found most houses had problems including the sensation with stuffy, hot, and fumes. Moreover, burning incense, using detergents, smoking and other behaviours cause the fumes problems.

Taiwan’s Ministry of the Interior announced that Taiwan has officially entered the stage of an “aged society” as Taiwanese people over 65 years old accounted for 14.05% of the country’s total population at the end of March. Therefore, the quality of Taiwan's long-term care institutions is receiving increasing attention.

Indoor pollution sources that release gases or particles into the air are the primary cause of indoor air quality problems. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the area. High temperature and humidity levels can also increase concentrations of some pollutants. If people stay in a building with poor ventilation, some health effects may show up shortly after a single exposure or repeated exposures to a pollutant. These include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue, which are called sick building syndromes (SBS) [2]. Other health effects may show up either years after exposure has occurred or only after long or repeated periods of exposure. These effects, which include some respiratory diseases, heart disease and cancer, can be severely debilitating or fatal [3].

The subjects for the long-term care institutions were the elderly population and disabilities. Ageing is associated with progressive decline in functional reserve of body organs [4]. There is an association between CO2 and SBS symptom prevalence [5-9]. The prevalence of upper respiratory symptoms, central nervous system symptoms were elevated due to CO2 exposure
In addition, the higher the CO₂ concentration, the higher is the likelihood of detecting airborne rhinovirus [11]. Many researchers found the high rates of self-perceived sickness and degree of physical impairment indicate a very dependent population, living in the long-term care residences for 2–10 years. Older people are more susceptible to the effects of indoor air pollution since they spend the large majority of their time indoors associated with a decline in immune defences and respiratory function [12].

In senior care facility, due to repeat suction and inadequate ventilation, aerosolization of secretions from tuberculosis patients is the main cause of tuberculosis [13]. Natural ventilation would cause positional relationship between the upper and lower sides of the household, and the concentration from upstream would accumulate in downstream at transient state [14]. The poor ventilation could also make the disease worse and increase the probability of disease outbreaks in long-term care institutions.

The common method for assessing ventilation efficiency are ventilation rate (L/s/_person) and air change rate (ACH). L/s/_person means volume of air entering the space per unit time per person; ACH means the ratio of the volume of air exchanged into a given space in an hour divided by the volume of that space for a positive pressure room or the exhaust airflow rate is used for calculation for a negative pressure room. L/s/_person emphasizes the pollution concentration, and conversely, ACH is based on the size of the space, it provides a small air exchange rate; the large space gets a large air exchange rate, and the size of some spaces is not proportional to the amount of pollutants generated. It will be more obvious that the L/s/_person ventilation standard is more suitable for health care institutions than ACH because the L/s/_person ventilation standard is easier to control and predict [15]. Although countries have ventilation standards for hospital, but there is no clear regulation on the ventilation of health care institutions. Thence, we take the ventilation standards for hospital as reference.

Menzies et al. (2000) found that the tuberculin conversion among clinical personnel was significantly more rapid and frequent among those working in average ventilation lower than 2 ACH. World Health Organization (WHO) indicated that based on this model, in situations of high quanta production (e.g. high-risk, aerosol generating procedures), the estimated probability of infection with 15 minutes of exposure in a room with 12 ACH would be below 5% [16]. The ASHRAE Standard 62-2010 gives the suggested value about 13 L/s/ person. Taiwan Centres for Disease Control suggests the air change rate of negative isolation rooms remain 8 to 12 ACH, bathroom and front room at least 6 ACH [17]. The ventilation studies reported relative risks of 1.5-2 for respiratory illnesses and 1.1-6 for sick building syndrome symptoms for low compared to high low ventilation rates [18]. On the other side, concentration uneven distribution commonly exists in a space, although it is still impossible to solve the problem of excessive concentration in some areas of the space, long-term care institutions with high exposure risks often have disease outbreaks. What's more, there are foreign studies using general ventilation to improve the single-person ward environment, and found that the temperature and humidity have improved, but after a while, there are still few bacteria remain indoors and cannot be completely excluded [19]. According to the result, the remained pollution may be the source of infection in wards; hence, general ventilation isn’t suitable for long-term care institutions.

Merely according to the suggested value to design the ventilation system may not make the space well indoor air quality since regulations were usually the minimum standard. Therefore, we need to develop a ventilation strategy to control CO₂ concentration and thermal comfort.

2. Material and Methods

2.1. Different Simulation Room

The numerical simulation room was set to 8.28 m * 5.84 m * 2.60 m as the simulation zone (Figure 1). The velocity inlet was set to diameter of a circle 0.35 m and an analysis flow of 0.052 m³/min; the flow direction is the z direction. The outlet was 0.02 m* 1.10 m in mode 1 and was a circle of 0.35m in diameter in mode 2.
2.2. Numerical Methods

We used the computational fluid dynamics (CFD) to investigate the indoor air flow. The equation 1 is the equation of the mass conservation.

\[ \nabla \cdot (\rho \mathbf{V}) = 0 \]  \hspace{1cm} (1)

The equation 2 is the momentum equation called Navier-Stokes equation.

\[ \rho \left( \frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} \right) = -\nabla p + \mu \nabla^2 \mathbf{V} \]  \hspace{1cm} (2)

For the study, the steady state is more meaningful than the transient state. Therefore, we modify the equation 2 to equation 3.

\[ \rho (\bar{\mathbf{V}} \cdot \nabla)\bar{\mathbf{V}} = -\nabla p + \mu \nabla^2 \bar{\mathbf{V}} + \bar{f} \]  \hspace{1cm} (3)

Mass transport equation was to calculate the CO2 concentration distribution in the study.

\[ \frac{\partial c}{\partial t} + (\bar{u} \cdot \nabla)c = D\nabla^2 c \]  \hspace{1cm} (4)

We used the commercial computational fluid dynamics (CFD) package FLUENT to model the system. FLUENT uses the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) described by Patankar [35], and we solve the complete Navier–Stokes equations of turbulence by using the realizable k-\( \varepsilon \) model, which is adequate for use in highly turbulent flows in the study.
2.3. Boundary conditions and hypotheses

Table 1 summarizes the boundary conditions imposed on the computational domain. The initial CO$_2$ concentration of the outdoor air was also set to 400 ppm. Furthermore, in accordance with (Scott et al., 2009), the CO$_2$ concentration of each exhaled breath was set as 5% (i.e. 50,000 ppm) and the breath flow rate was given as 0.01 m/s. The bedroom air inlet flow rate, which referred ASHRAE IAQ Standard 62-2010, was set as 52 L/s (i.e. 13 L/s per person, 4 people) in the simulations. Finally, the number of people was 4. In performing the simulations, the following hypotheses were applied:

1. The fluid was incompressible Newtonian fluid.
2. The flow field had a three-dimensional turbulence.
3. The effects of buoyancy were sufficiently small to be ignored.

| Parameter                              | Set value          |
|----------------------------------------|--------------------|
| Bedroom air inlet flow rate            | 52 L/s             |
| Breath flow rate                       | 0.01 m/s           |
| CO$_2$ concentration of bedroom air supply | 400 ppm          |
| CO$_2$ concentration of breath         | 50,000 ppm         |
| Number of people                       | 4                  |

3. Results and Discussions

3.1. Experimental process

Table 1 summarizes the boundary conditions imposed on the computational domain. Figure 2 presents our experiment process.

1. Investigation: selecting the subjects for this experiment and analysing current environmental problems in long-term care institutions
2. Flow Simulation: using ANSYS-Fluent software to simulate different conditions
3. End of the Investigation

3.2. Results and discussions

Figure 3 presents the simulation results about CO$_2$ distribution. Observing the streamline on x-z plane near human body, the recirculation zone developed up while main airflow didn’t flow through. The recirculation zone characteristics, which are lower velocity and lower pressure, could cause CO$_2$ accumulation.
Model 1

Model 2

**Figure 3.** The CO₂ concentration distributed in room.

**Figure 4** compares the performance of eliminating CO₂, there obviously found model 2 is better than model 1. However, the CO₂ concentration in the space maintained higher than the level of 1,000 ppm, which was higher than the regulatory standards meanwhile. The movement of CO₂ followed the flow stream.

*Figure 4. The relationship between the variation of CO₂ concentration and vertical distance (locate on line a and b).*

In these simulated results, we found that regardless of the position of air supply, the flow barely moved below and the CO₂ concentration did not have fully-mixed since the pathway of flow steam only passed through above, closing to the ceiling. Therefore, the CO₂ released from mouths accumulated around the head.

4. **Conclusion**

Comparing different air supply positions, we found the CO₂ concentration still maintained high level. From the results of simulations, we found the alternate air supply configuration is not sufficient in controlling the high level of CO₂ concentration exposures to the residents. For the most part, we could
inference that general ventilation may not be the best ventilation system for long-term care institutions. If simply using natural ventilation, the concentration distribution may be much uneven. Thus, using local exhaust ventilation may be much efficient and save more energy than other ventilation system.

References

[1] Klepeis, N., N. WC, et al. 2001 Journal of Exposure Analysis and environmental Epidemiology The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants. 11 231-252.

[2] Ferng, S. F., and Lee, L. W. 2002 J. Environ. Health Indoor air quality assessment of day care facilities with carbon dioxide, temperature, and humidity as indicators 65 14–8, 22.

[3] United States Environmental Protection Agency-Introduction to Indoor Air Quality. From: https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality

[4] Boita, F. et al. 2006 Intergroupe Pneumo Geriatrie SPLF-SFGG. Rev. Mal. Respir. Evaluation of pulmonary function in the elderly 23 619–28.

[5] Environment Protection Bureau, Pingtung Country. From: http://ptiaq.huan-yu.com.tw/

[6] Apte, M G Fisk, W J and Daisey, J M 2000 Indoor Air Associations between indoor CO2 concentrations and sick building syndrome symptoms in US office buildings: an analysis of the 1994-1996 BASE study data 10 246-57.

[7] Kinshella, Michele, et al. 2001 Applied Occupational and Environmental Hygiene Volume Perceptions of Indoor Air Quality Associated with Ventilation System Types in Elementary Schools 16 952-60.

[8] Erdmann, Christine A and Michael G 2004 Indoor Air Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100 - building BASE dataset 14 127-34.

[9] Norbäck D, Nordström K 2008 Int Arch Occup Environ Health Sick building syndrome in relation to air exchange rate, CO (2), room temperature and relative air humidity in university computer classrooms: an experimental study 82 21-30.

[10] Reynolds S J, Black D W, Borin S S , Breuer G, Burmeister L F, Fuortes L J, Smith T F, Stein M A, Subramanian P, Thorne P S, Whiten P 2001 Applied Occupational and Environmental Hygiene Indoor environmental quality in six commercial office buildings in the Midwest United States 16 1065–77.

[11] Myatt T A, Johnston S L, Zuo Z, Wand M, Kebadze T, Rudnick S, Milton D K 2004 Am J Respir Crit Care Med. Detection of airborne rhinovirus and its relation to outdoor air supply in office environments 169 1187-90.

[12] Ana M, Ana L P, Pedro Carreiro-Marins et al. 2016 Age and Ageing The impact of indoor air quality and contaminants on respiratory health of older people living in long-term care residences in Porto 45 136–42.

[13] Yi-Shen C 2007 The Effects of Ventilation Improving Measures for Senior Care Facility on Indoor Bio-aerosol Level Mitigation

[14] Alireza Kermani 2015 CFD Modeling for Ventilation System of a Hospital Room

[15] Wen-Xing L 2004 Energy Information Network Energy Conservation Experts Field Investigation of the Ventilation Rate of Health Care Facilities and Introduction ASHRAE STANDARD 62-1999.

[16] Atkinson et al. 2009 WHO: Natural ventilation for infection control in health-care settings.

[17] Centre for Disease Control Department of Health Taiwan R.O.C. Manual of Standard Operation Procedure of isolation rooms. From: https://www.cdc.gov.tw/infectionreportinfo.aspx?treenid=075874dc882a5bfd&nowtreenid=91977f9e601db75&tid=4775659102DE26C1

[18] Seppänen O A, Fisk W J, Mendell M J 1999 Indoor Air Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings 9 226-52.

[19] C C Lai, Y.-C. Hsieh, Y P Yeh, R W Jou, J T Wang, SbL Pan, and H H Chen 2016 Epidemiol Infect A pulmonary tuberculosis outbreak in a long-term care facility 144 1455–62.