CFD SIMULATION OF INTER-FLAT AIR CROSS-CONTAMINATION—A POSSIBLE TRANSMISSION PATH OF INFECTIOUS DISEASES

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ABSTRACT

The objective of this study is to investigate the possible transmission mechanism of inter-flat air cross-contamination under the condition of single-sided natural ventilation. In high-rise residential building with flush windows on the same side, the air pollutants can diffuse from lower flat to adjacent upper flat in the vertical direction related to the inter-flat air flow through open windows caused by the temperature difference between the indoor air and the air outside of the windows. Based on the validation of CFD models with experimental data given by Heiselberg, the renormalization group (RNG) based $k-\varepsilon$ model, together with Carbon dioxide (CO_2) used as a tracer, is chosen to reveal this air cross-contamination. Different effects of contamination spread into upper room were evaluated through kinds of cases performed in various conditions. The numerical results demonstrate this possible transmission path.

KEYWORDS

single-sided natural ventilation, CFD simulation, cross contamination, high-rise residential building

INTRODUCTION

Understanding the characteristics of contaminant distribution in different indoor environments and the mechanisms of contaminated indoor air diffusion in buildings is the prerequisite conditions of employing indoor air pollution control strategies (e.g. engineering controls). Detailed information of contaminant spread and concentration distribution in building environment, which is one of the main subjects of indoor air quality control, has become of great concern for the modern society as more and more various kinds of buildings arise along with sustainable development in the building industry. In recent years, with more and more people live in large and crowded cities in many parts of the world, the risk of contaminant dispersion, in particular the potential hazard for residents in airborne transmission of infectious diseases in the high-density residential buildings located in densely populated area has received increasing attention.

Hong Kong's indoor environmental problems are typical of those in many densely populated cities. Especially many unwanted consequences come with more and more high-rise residential buildings raised in Hong Kong (Niu 2004). The objective of this investigation is raised from the attractive phenomenon exposed in the worldwide scale outbreak of the SARS (Severe Acute Respiratory Syndrome), focused on the vertical transmission pattern in high-rise residential buildings observed during the SARS epidemic period. Two serious case clusters occurred in Hong Kong drew much attention to the mode of transmission of SARS virus in these two environmental factors (Li et al. 2004a, Li et al. 2004b). Besides these two super-spreading events with considerable investigations, less scale SARS clusters occurred in several other high-rise residential buildings in Hong Kong have not devoted sufficient attention. In Wing Shui house (Lek Yuen Estate, Sha Tin District), 11 infection cases residing in 5 households were reported with no presence of SARS virus detected in sewage system and common areas after prompt investigation, which eliminated the possibility of spread through re-entrance space that was highly publicized before (Anon.A). In Hing Tung House (Tung Tau Estate, Kowloon City), 6 confirmed SARS cases involving 3 families were reported along one vertical block with findings showed that this building did not have any structural factors similar to those in relation to the Amoy Gardens that would lead to an outbreak (Anon.B). Especially in the case of Wing Shui house, adjacent upper floor residents were infected after those on the lower floor and bio-material of SARS virus was found within the deposits on the window-sill and floors at two other upper floors. In view of these facts, it is well justified to suspect that the travel of the virus-containing contamination with ventilation air from lower flat to the adjacent upper flat in high-rise residential blocks at certain environmental conditions can be a spread path.

In this paper, inter-flat air-flow at one-sided ventilation conditions will be simulated to examine one of the most likely virus-laden contaminations spread mechanisms which has been overlooked so far. The preliminary findings has been revealed by Niu et al. in the former studies (2005). The hypothetical flow pattern in adjacent two flats in the vertical direction is shown in Figure 1. The exhaust air coming out from the upper part of the window on the lower floor will re-enter the lower part of the open window at the immediate upper floor. This phenomenon termed natural ventilation is created by pressure differences between the inside and outside of the building induced by wind and air temperature differences. In view of the weather condition during the SARS epidemic period, the temperature of outdoor environment was lower, while the indoor temperature was higher due to isolation, and the openable window separates two spaces at different temperatures. While door closed, with the residents' behavior of window opening owing to themselves uncomfortable feelings about the indoor air quality, the flats become one-side ventilated induced by air temperature differences. Our hypothesis is that, on relative calm days when wind speed is low, single side natural ventilation through the open windows dominates the air flow pattern from one flat to another flat as described above will be possible a major role in virus-laden contaminations transmission. The simulation results demonstrate that the infectious contaminated-air diffuse from the lower flat and re-enters the immediate upper flat.

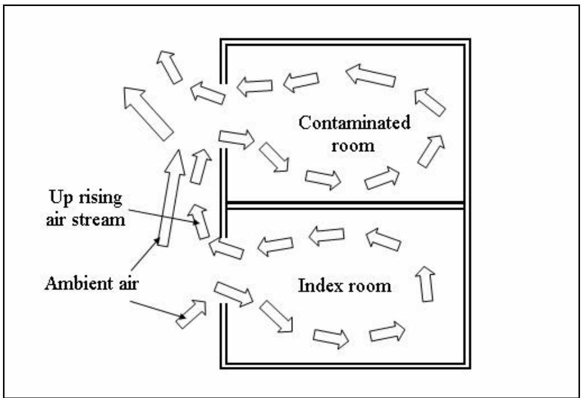

Figure 1 Possible transmission route

RESEARCH METHODS

Models Validation

Based on the hypothesis and the weather conditions during the SARS epidemic, the worst scenario for the transmission of infectious diseases could probably happened in the circumstance analyzed above, under the force of temperature-driven single sided natural ventilation. Therefore, study on the mechanisms of this kind of ventilation is the prerequisite to investigate the potential spread path of infectious disease. CFD methods (Launder and Spalding 1974; Niu and Kooi 1992) are employed in these studies on account of its great abilities to predict parameters such as flow, temperature, species concentration in great details. Considering about the potential transmission route is mainly dependent on the driving forces under single-sided natural ventilation caused by windows opening, the CFD program is first compared with experimental data conducted in similar situations to acquire confidence in the use of the predictive tool.

The validation model was based on the experiments conducted by Heiselberg et al. (2003) performed in Denmark, which was aimed at air flow distribution in and around a single-sided naturally ventilated room. The test chamber which was regarded as an outdoor environment was simulated by means of a fictitious volume that was suitably ventilated and enclosed by solid walls (Perino and Heiselberg 2003).The standard and RNG $k-\varepsilon$ models, together with buoyancy production terms plus standard wall function were employed to evaluate the extent of turbulence prediction affecting the indoor airflow. Fixed temperatures equal to designed indoor temperature were imposed on the internal wall of the test room in view of the lag effects in the experiments after the heater were switched off. The inlet air flow (cold air) with the same ventilation quantity as the experiment was set on the narrow zonal areas far away from the test room, in order to wipe off influences on the air exchange through the opening by outside flow. The schematic of the test room and typical points are shown as Figure 2.

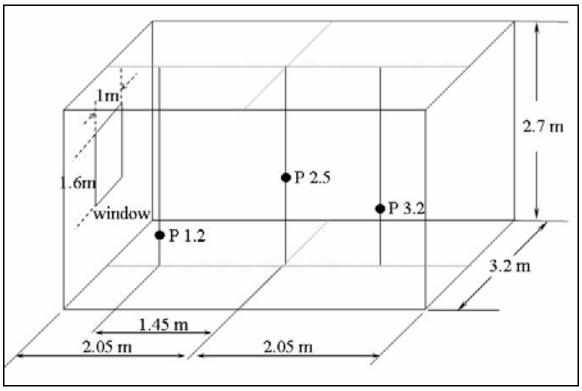

Figure 2 Schematic of the test room and points

Following the validation were presented in different temperature differences between outdoor and indoor, $\Delta T = 20$ ℃ and $\Delta T = 10$ ℃ , respectively. Comparisons between experiment and simulation results were performed in 600 seconds since the window was opened. The ventilation rate in the numerical simulations can be computed by integrating the velocity in Y direction at the opening.

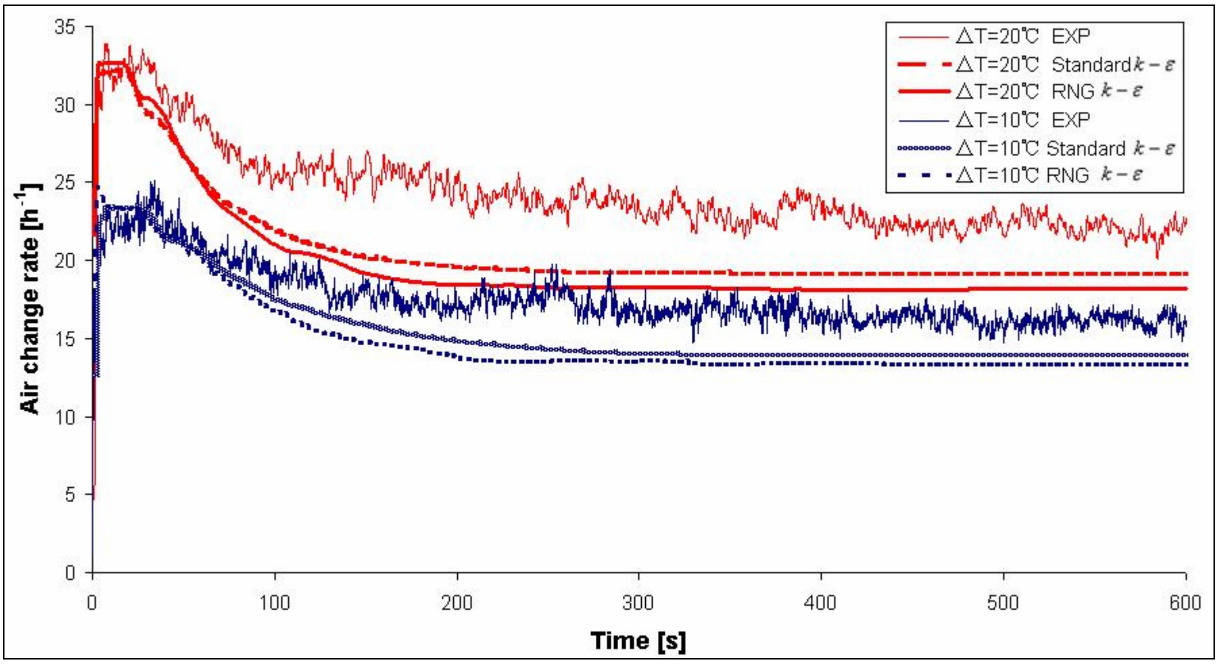

Figure 3 Comparisons of ACH predicted by different models with experiment data

Figure 3 plots the measurement ACH and the predicted results obtained by standard and RNG $k-\varepsilon$ models vary with time under two temperature differences conditions. The flow characteristics are basically illustrated by the numerical results. High-ACH were obtained nearly after the windows were opened, and then decreased gradually over time, finally turned into the quasi-steady state and didn't change much in the latter period of the process. It is shown that CFD results calculated by both models agree well with the experimental data in former period of the process while deviate from it in latter period. ACH is under predicted by both models in quasi-steady state period. This discrepancy thought to be explained by the different heating up methods applied in the experiments and simulations. Internal heaters were used to keep the average indoor and outdoor air temperatures reach the desired value, and then were turned off and the experiment started with the window opened, which should gave rise to a possibly higher temperature than desired value induced by the lag effect of the heaters. While the fixed values exactly equal to the desired values are set in the simulations. These differential heating methods lead to the unequal temperature differences between indoor and outdoor and contribute to the differences of the driving forces of air exchange in experiments and simulations.

The predicted and respectively experimental velocity magnitude in different typical points is shown in Figure 4 and Figure 5. Good agreement was achieved between both model predictions and the experiment data despite of the fluctuant characteristics which could not be revealed by the inherent time-averaging modeling approach. In particular, the results obtained

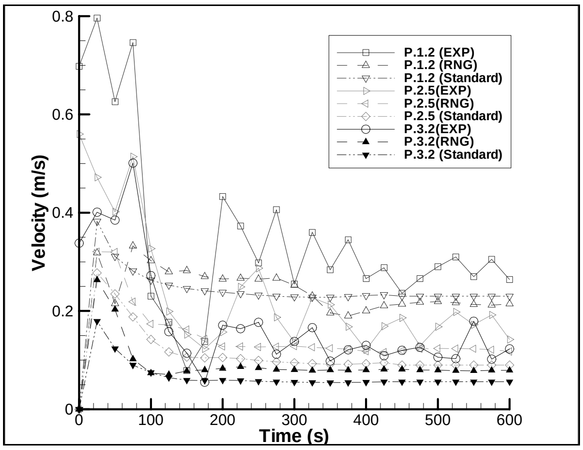

Figure 4 Comparisons between predicted velocities and experimental data at different points($\Delta T = 20$ ℃)

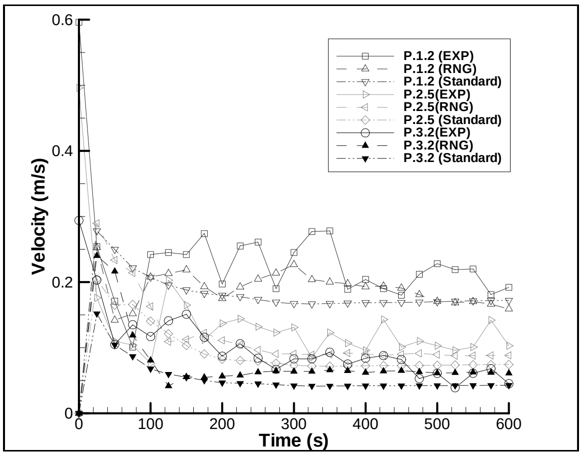

Figure 5 Comparisons between predicted velocities and experimental data at different points($\Delta T = 10$ ℃)

by RNG $k-\varepsilon$ model are more close to the measurements, especially in the low-velocity field such as point 2.5 and 3.2. The possible explanation is that the RNG $k-\varepsilon$ mode using differential viscosity model take the effective Reynolds number into account. And the standard version of the $k-\varepsilon$ model inadequately predicts the turbulence energy, k , in recirculation zones . Through its effect on the viscosity, the local velocity distribution may be different from the actual distribution.The comparisons illustrate that standard and RNG $k-\varepsilon$ is both suitable in predicting this kind of single-sided natural ventilation generated by temperature differences between outdoor and indoor environment. In particular, the RNG $k-\varepsilon$ model gave better performance than standard $k-\varepsilon$ model in velocity prediction, especially in the centre of the room, where large recirculation exists in the case of an empty room, RNG provided better predictions than the standard $k-\varepsilon$ model. The indoor velocity field strongly influenced the spread of indoor contamination. Therefore, RNG $k-\varepsilon$ model is employed in the following application studies.

CFD Simulation

The infectious contamination generated by index patient in lower floor was simulated by carbon dioxide (CO_2) as passive tracer. Considering that indoor airflows are always a feature with low characteristic velocities and the contaminant particles are with small diameters, the Stokes Number for the contaminant particles flow indoor is far less than unity and the particles act like gas tracers (Tian et al. 2006). Hence, it is appropriate to employ CO_2 as a gas tracer to investigate the possible transmission path of infectious contamination.

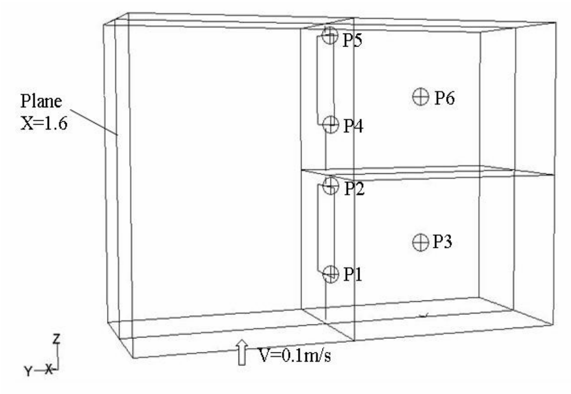

Figure 6 Schematic of geometry in the simulations

To simplify the following investigations, sampled room in the absence of any furniture was performed during the studies. The Schematic of Geometry is shown as Figure 6. The wind velocity profile near to a tall building can be particularly complex caused by the interaction between meteorological conditions and building structures. One of the possible wind directions is along building sides owing to the characteristics of high-rise buildings. According to the classification criteria of wind speed in meteorology, low to $0.1m/s$ wind speed which means “no wind” conditions along the positive direction of z axis was set as the inlet of the whole domain to approach the natural outdoor environment.

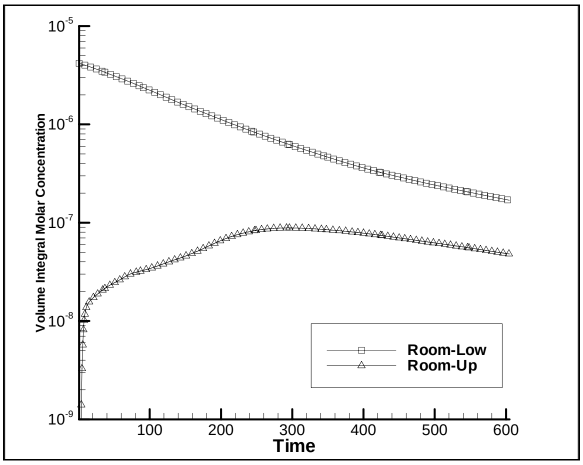

Figure 7 Predicted volume-averaged CO_2 concentrations of each room versus time

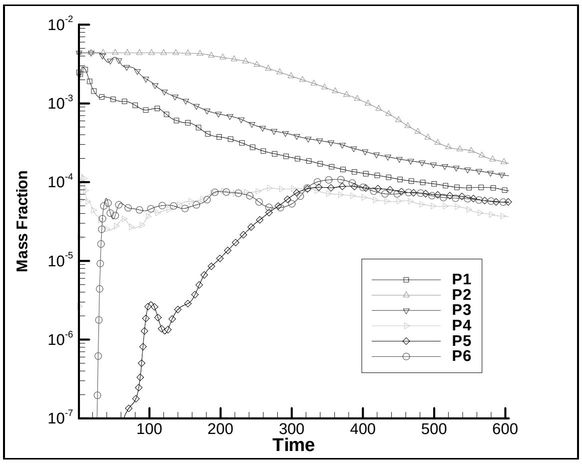

Figure 8 Simulated CO_2 mass fractions at different points versus time

performed to illustrate the transient spread of contaminants from index room located in lower floor. The temperatures of indoor and outdoor were set to 25.5℃ and 19℃, respectively. The simulation starts with the windows of both rooms are opened, and lasts for 600 seconds. Significant concentration of contaminant can be obviously detected through the predicted results after time elapsed, as shown in Figure 7. Considering about CO_2 is clean in other areas, it is evidently suggested that the contaminated air of lower room exhausted from the window could re-enter the upper room. The contaminant concentration in upper room continuously increased in the first half of the period, since the contaminated effect was dominant in this part of time. Subsequently became to decrease in the second half of the period, which meant the dilute effect was dominant in this part. The concentration of contaminants in lower room was continuously decreased owing to the dilute effect along with free decay procedure. Figure 8 illustrated the changing procedure of contaminant concentrations at several points located in typical places within the rooms. It records the concentrations of contaminants in different areas vary over time. The concentrations at P4 increased immediately after the simulation began, followed by the increasing of P6, and P5 began to slowly increase after a while. After an elapsed time, the concentration of these three points achieved approximately the same due to the mixing effect of the upper room. The contaminant concentrations of Point P1, P2 and P3 (hereafter denoted as C_{p_1}, C_{p_2} and C_{p_3}, respectively), which were located in the lower room, decreased after the beginning due to the air change from outside. C_{p_1} evidently reduced at the very start since it is near to the entrance of the fresh air. C_{p_2} remained little change at the beginning of the period, as a result of stratification of the contaminant induced by the temperature differences. C_{p_3} began to decrease after a little while from the beginning, since P3 was located in the middle of the room and the flow velocity in this area is weak.

Another case was conducted in steady-state with a contamination source located in the middle of the lower room. The objective of this case is to evaluate the possible infectious risk when there is a continuous contamination source located in the lower room which could probably happen when an infectious patient lives in that room. The layout of the simulation domain is the same as described above.

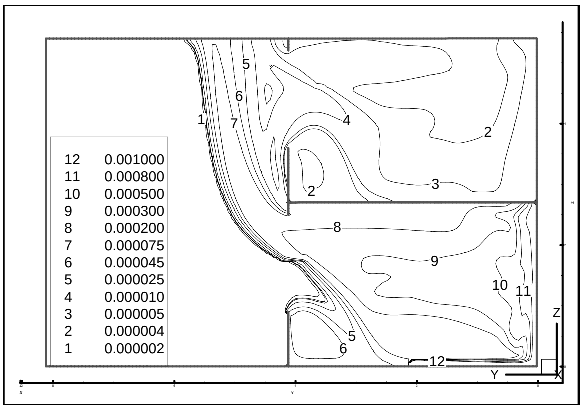

Figure 9 Simulated CO2 concentration distributions at the centre plane (X=1.6m)

The windows of both rooms were opened during the simulations. The contaminant (CO_2) is constantly released from the bottom of the lower room, at a flow rate of 5ml/s.Fig. 9 shows the predicted distribution of CO_2 concentration at the mid-plane of the model rooms. The predicted concentration profile was a simple representation of contaminations spread between two vertical adjacent rooms. It can be obviously observed that the contaminated air exit from the upper part of the lower window and re-enter the upper room. CO_2 was emitted from the source and dispersed in the lower room, then exhausted from the window and moved upward owing to the buoyancy effects, finally re-enter the upper room as mixing of supplied air by natural ventilation. It is approximately lower about two orders of magnitude of the overall CO_2 concentration in upper room than that is in the lower index room.

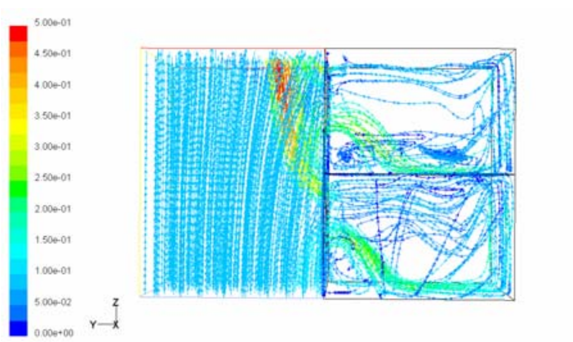

Figure 10 Simulated path line colored by velocity

Fig. 10 presents the predicted flow path line colored by velocity magnitude. The distribution of CO_2 concentration is mainly dependent on the flow route in the simulated domain. This illustrates both the flow pattern in the simulation domain and the velocity distribution. The prediction flow pattern indicates that the hypothetical airflow route as shown in Fig. 1 was practically reasonable. The predicted results of flow field are consistent with the distribution of CO_2 concentration, the cold fresh air enter the lower room and combined with the contaminated air, than exit through the window and moved upward to the intake of upper floor.

DISCUSSION

The assumed case performed in unsteady-state illustrated the potential transmission path through contaminated lower room to the adjacent upper room in vertical direction. The variations of overall concentration in each room, together with the concentration changing at individual points, demonstrate that in high-rise residential buildings under certain meteorological conditions, the upper room could be influenced by the lower room with a significant contaminant concentration. Based on the prediction results obtained in steady state, it can be obviously seen that indoor contaminants source located in the lower floor can be the main contributors to concentrations in vertical adjacent upper room under certain meteorological conditions. The magnitude of the overall CO_2 concentration in upper room could be two orders lower than that is in the lower index room under low wind speed conditions. Designers of high – rise residential apartment buildings may have long overlooked the cross-contamination of the ventilation air. Possible optimization design for building structures could be presented to reduce this kind of cross contamination.

CONCLUSION

The numerical results performed in this study corroborated the hypothesis that the travel of the virus-containing bio-aerosols with ventilation air from lower flat to the adjacent upper flat via open windows can be a spread path. Different effects of contamination spread into upper room were evaluated through kinds of cases performed in various conditions. The prediction results possibly explain the presence of bio-material of SARS virus at two other upper floors, represented by Wing Shui Building, Shatin, during the SARS epidemic period. The features revealed by the investigation indicate that early intervention for high-rise residential blocks in terms of diagnosis and isolation should be performed once after the outbreak of an infectious disease. The identification of this transmission path also shed light on ventilation design in high-rise residential blocks to avoid cross indoor air contamination.

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