THE UNIVERSITY OF HONG KONG

香 港 大 學

Our ref.: E5/8/21

December 5, 2003

Miss Flora TAI
Clerk to Select Committee
Legislative Council Secretariat
Room 608, 6/F, Citibank Tower
Garden Road
Central
Hong Kong

Dear Miss TAI,

Select Committee to inquire into the handling of the Severe Acute Respiratory Syndrome outbreak by the Government and the Hospital Authority

I refer to your letter to Mr. P.K.K. Lee, Head of Department of Civil Engineering of HKU, received on November 28, 2003, and am pleased to provide you with the following research papers:

1. *Li, Y., Chan, A., Leung, D. and Lee, J.H.W.:* Dispersion and control of SARS virus aerosols in indoor environment - transmission routes and ward ventilation. Keynote paper, National Conference on New Advances in Air-conditioning and Refrigeration, Shanghai, 18-22, November, 2003 (Annex I); and

2. *Li, Y. and SARS-Busters:* Experimental investigation of the SARS busters' new air-conditioning system for SARS wards. Presented the 7th Asia Pacific Conference on Built Environment, Hong Kong, 18-19 November, 2003 (Annex II).

I hope that they are of use to you. Further investigations into the transmission routes of SARS are underway and relevant reports will be submitted to the Select Committee when available.

Should you have any questions or require further information, please do not hesitate to contact me (Tel. No.: 2859-2801) or Ms. Eunice Chan of my Office (Tel. No.: 2857-8259).

Yours sincerely,

(Mrs.) Angela Tsang
Faculty Secretary

Encls.

c.c. Mr. P.K.K. Lee, Head of Department of Civil Engineering, HKU
Professor J.H.W. Lee, Department of Civil Engineering, HKU
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DISPERSION AND CONTROL OF SARS VIRUS AEROSOLS IN INDOOR ENVIRONMENT - TRANSMISSION ROUTES AND WARD VENTILATION

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ABSTRACT

The severe acute respiratory syndrome (SARS) epidemics in Hong Kong and elsewhere between November 2002 and June 2003 have left us an unanswered question – were the SARS virus transmission airborne in some of the super spreading events? Before the epidemiological answer to this question becomes available, it is important that we consider the possibility of airborne transmission when dealing with environmental control measures such as air conditioning and ventilation design in SARS wards. Epidemiological studies on the Amoy Gardens outbreak and the 8A ward outbreak in the Prince of Wales Hospital have shown that the possibility of airborne transmission cannot be ruled out at the time of writing this paper (i.e. August 2003).

SARS virus-laden aerosols and/or droplets can be originated from coughing, sneezing and breathing of a patient, or even produced by an aerosolizing process with input of faeces or urine of a patient. Not taking into account of the infectivity of the virus-laden aerosols, the dispersion and evaporation of aerosols in and around buildings can be analyzed and experimentally studied. With sizes of between 0.5 and 10 μm in diameter, the aerosol particles can easily drift in an airflow current and stay in air for a long time. This has significant implication to transmission routes of the virus as well as air conditioning and ventilation system design in buildings, in particular in hospitals.

Working in a team of experts with a background in fluid dynamics, air pollution, and epidemiologists, we have participated in the HKU Faculty of Engineering's research team in investigating the transmission routes in the Amoy Gardens outbreak, where more than 300 people were infected around 19 March 2003. Based on theoretical, computational and experimental studies, a plausible hypothesis has been proposed on the transmission routes for Flats 7 and 8 in Block E, other flats in Block E and other blocks in the Amoy Gardens.

HKU was also commissioned by the Hong Kong Institution of Engineers (HKIE) in late May 2003 to construct a full-scale mock-up test chamber for SARS wards and to investigate the performance of a new air-conditioning system designed by the HKIE SARS-Busters. Adopting a modular design, the new full-scale test room can also be used for testing other types of hospital rooms such as intensive care units (ICUs), fever wards and single-occupancy SARS wards etc. The full-scale test room was completed in less than 4 weeks time between late May and mid-June 2003. The air-conditioning system tests were completed in another four weeks time between mid-June and mid-July 2003. The new air conditioning system is found to perform well for a nearly realistic full-scale SARS ward.

Key words: Transmission routes, aerosol dispersion, SARS wards, hospital ventilation, local exhaust, test room.

1. INTRODUCTION

As the first severe and easily transmissible new disease emerged in the 21st century, the epidemics of the severe acute respiratory syndrome (SARS) disease between November 2002 and June 2003 resulted in unprecedented international efforts in controlling the disease coordinated by the World Health Organization (WHO). A total of 8422 reported probable cases and 916 deaths are reported in 34 countries and/or regions (WHO, 2003a). On 5 July, WHO announced that the chain of transmission appeared to be broken.

The disease spread to the rest of the world by a visiting Guangdong infected medical doctor to Hong Kong, where the doctor stayed in a hotel and infected at least 14 guests and visitors in the hotel from Hong Kong, Canada, Viet Nam and Singapore etc.. Possibly due to the unawareness of the disease, most of these infected individuals have sparked large outbreaks in hospital systems. An unprecedented travel advisory was issued by WHO on 15 March. The epidemic has caused a significant impact on the regional economy and health-care systems, e.g. in Hong Kong.

Peiris et al (2003) first identified a coronavirus as the cause of the severe acute respiratory syndrome. SARS virus has been a mysterious and rather contagious virus. It is believed to be mostly spread by close person contact, in particular exposure to droplets of respiratory secretions from an infected person. Contamination of inanimate materials or objects by infectious respiratory secretions or other body fluids (e.g. saliva, tears, urine and feces) may play a role in disease transmission; see Tsang (2003). Tsang (2003) also suggested that SARS transmission via fecal droplets is uncommon but can result in large outbreak if given the right combination of circumstances.

One of the most intriguing characteristics of the 2003 SARS epidemic is the occurrence of super spreading events (SSEs). A super-spreading event refers to a large cluster of infection in which one or more individuals disproportionably infect many more other individuals than an average SARS patient. WHO (2003b) has explained that the super-spreading phenomenon may be due to the lack of stringent infection control measures in hospitals during the early days of the epidemic, which could not explain some of the identified SSEs so far, e.g. the Amoy Gardens outbreak in Hong Kong.

In some of the super spreading events, building environmental systems have been considered and shown to play significant roles in virus transmission. There has been a wide range of media coverage of inadequacy of air-conditioning systems in hospital wards, failure of the drainage system in a large apartment building estate in Hong Kong, various suggestions for improving ventilation systems and virus source control systems in hospitals etc. This wide range of media coverage demonstrated the concerns shared by the hospital care workers, the public as well as the Government,

This paper discusses the transport of SARS virus-laden aerosols in indoor environments and associated control methods. We provide examples of research in these areas that have been carried out in the Department of Mechanical Engineering at the University of Hong Kong since the outbreak in Hong Kong. Most of our work are related to the transmission routes of the virus in large outbreaks, how to improve building design, transmission dynamics of super spreaders, SARS ward air-conditioning, and local ventilation for virus source control etc. Most of the work are still on-going. Only preliminary results are presented here.

2. CHRACTERISTICS OF SARS VIRUS AEROSOLS DISPERSION

Past studies on transmission routes for communicable respiratory infections have been reviewed by Barker et al (2001) for community facilities and domestic homes, by Mendell et al (2002) for working places such as offices and by Cole and Cook (1998) for health care facilities. Some other respiratory viruses, such as those causing common cold and flu, can spread from an infected person to a new host by airborne aerosol inhalation, contacts by hands, such as hand shaking and by touching contaminated surfaces. Most studies on airborne transmission of various respiratory viruses are not as conclusive as for person-person, or person-surface-person transmissions.

As the SARS coronavirus is novel, a complete picture as to how SARS was transmitted is still not clear. Evidences so far suggest transmission by respiratory droplets and direct contact with a patient's secretion. Scientists in the WHO network of collaborating laboratories confirm that the SARS virus can survive after drying on plastic surfaces for up to 48 hours, in faeces for at least 2 days, and in urine for at least 24 hours. The SARS virus in faeces taken from patients suffering from diarrhoea, which has a lower acidity than normal stools, has been shown to be able to survive for 4 days.

The virus-laden aerosol flows in indoor environments can be analyzed and predicted(Young and Leeming, 1997), although it is difficult. The sizes of droplet nuclei due to sneezing, coughing and talking are likely to be a function of the types of virus, the generation process and the environmental conditions. Sneezing can generate approximately a million droplets of up to 100 μm in diameter, plus several thousand larger particles formed predominantly with saliva from the front of the mouth. As these droplets are emitted, they start to evaporate and thus change their masses and sizes, and sufficiently small droplets (0.5 to 12 μm) could be airborne. Thus, if large droplets are settled originally due to their gravity, they can be re-suspended as they evaporate and become smaller. The actual size distribution of droplets is also dependent on parameters such as the exhaled air velocity, the viscosity of the fluid and the flow path (i.e. through the nose, the mouth or both). Compared to the ambient air velocities in an air-conditioned room, which is about 0.25 m/s for thermal comfort requirements, the settling velocities for these droplets are extremely low, between 0.2 and 1.2 m/h (i.e. 0.05 to 0.3 mm/s). The average air speed in an air-conditioned room is designed to be less than 0.25 m/s. Typical supply air speeds at the supply grilles can be as high as 2-4 m/s. As a result of the small sizes, drift of the droplets is more dependent on the turbulent air flow than on gravity.

Brundrett (1992) found that the rate of evaporation was dependent upon the ambient humidity. Evaporation of droplets is a fundamental process in aerosol dynamics. They are important in atmospheric aerosol studies, cloud microphysics, nuclear reactor safety, combustion and spray (Beck and Watkins, 2003) etc, involving simultaneous heat, mass and momentum transfer between droplets and surrounding gas. Momentum transfer determine the particle motion, mass transfer results in droplet size changes and heat transfer causes the changes in the droplet temperature. As the indoor relative humidity is generally controlled to be between 50-60% in an air-conditioned room, the droplet sizes reduce rapidly once released into the air, see Figure 1.

It is known that the evaporation of liquid droplets containing small solid particles (in this case, the virus particles) has two processes, i.e. the rapid evaporation process as the amount of liquid mass decreases and the droplet diameter continuously shrinks, and the critical evaporation process after the critical solid-liquid mass ratio is reached, i.e. the discrete insoluble solid particles form an agglomerate (or cannot contract anymore), while the voids between particles are still filled with liquid. During the second process, the drying rate is not large. It is possible that after the second stage, the particles may be fragmented, i.e. breaking apart from each other (Elperin and Krasovitov, 1995). However, there have not been any systematic studies of evaporation of droplets due to coughing, sneezing and breathing.

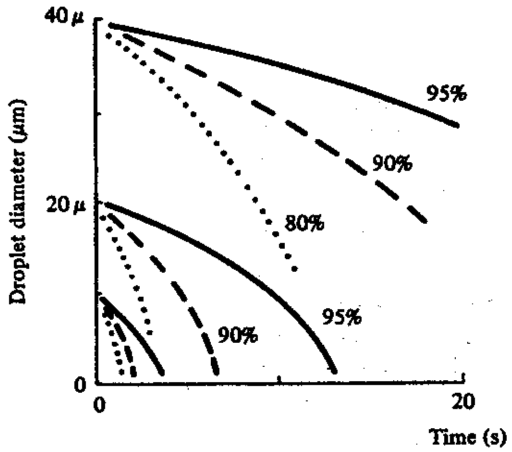


Figure 1. Changes in water droplet size with different ambient relatively humidity (Adapted from Brundrett (1992)).

3. EXAMPLE 1 – TRANSMISSION ROUTES IN THE AMOY GARDENS OUTBREAK

Between 21 March and 1 April 2003 more than 200 residents in the Amoy Gardens housing estate in Hong Kong were infected with SARS. The infection cases were not randomly distributed. Most occurred in certain blocks and at certain levels, and evidently conformed to a pattern, see Figure 2. Both the HKSAR Government and the WHO investigated the possible virus sources and transmission routes shortly after the Amoy Gardens outbreak. Although their investigations suggested several possible transmission routes, none of them fully accounted for the infection patterns. Preliminary research findings by the Faculty of Engineering team have identified the major virus source from the drainage stacks and revealed a strong correlation between the infection pattern and air flows in the re-entrant, air flows between flats in Block E, and wind flows between blocks.

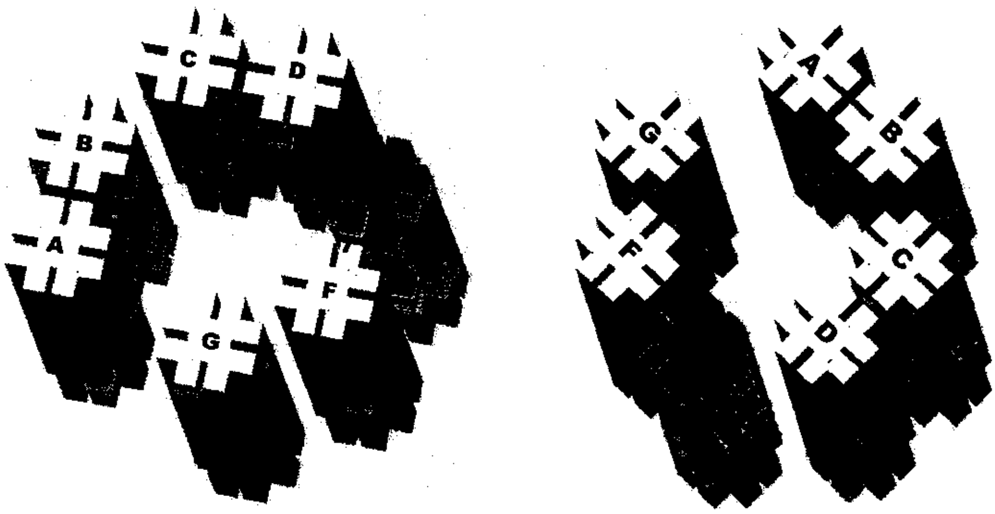


Figure 2. Distribution of the infected flats in the Amoy Gardens between 21 March and 3 April. Flats 7 and 8 in Block E were mostly infected. Flats 1-4 in Block E were moderately infected, while Flats 5 and 6 had fewer infections. Blocks B, C and D were infected in some concentrated areas. Most other wings were not inflected.

The Hong Kong Government (2003) first presented on 17 April 2003 its main findings of the investigation and suggested that the environmental factors played a major role in this outbreak. Most of the Amoy Gardens patients had diarrhea, contributing to a "significant virus load being discharged in the sewerage in Block E, the worst infected building block. The index patient was suggested to first infect a small group of residents within Block E, and subsequently to the rest of the residents in that block through the sewage system, person-to-person contact and the use of shared communal facilities such as lifts and staircases. These residents subsequently transmitted the disease to others both within and outside Block E through person-to-person contact and environmental contamination. After three weeks investigation, the WHO investigation team (2003) suggested that the backflow of virus-laden droplets into the bathroom, which then entered the re-entrant (light well) and upper storey apartments through open windows. Peiris et al (2003) presented a prospective study of 75 patients from this outbreak and suggested the possibility of oral-faecal transmission based on the findings of the presence of virus in the stool. Some discussion on the Amoy Gardens outbreak was also included in Donnelly et al (2003).

The suspected index patient is considered to be a super spreader. He visited a flat in Block E twice on 14 March and 19 March 2003 respectively. Our simulation shows that his second visit coincides well with the predicted exposure dates. More than 200 residents of Amoy Gardens Block E are put in isolation at two holiday camps on 1 April.

Our environmental investigations are carried out by an inter-disciplinary approach, with expert input from aerosol science, thermo-fluid dynamics, and mechanical engineering systems in buildings. We have adopted an integrated theoretical analysis, laboratory testing and computer simulations. We include a detailed study of drainage systems using a laboratory full-scale test model, a study of aerosol generation process in both the laboratory and field measurements in a similar flat to Amoy Gardens (Figure 2), and computational fluid dynamics simulations. Accurate modelling of the air flows and virus-laden aerosol dispersion is difficult, in particular when dealing with wind flows over a complex building estate. The virus-laden aerosol dispersion in the Amoy Gardens outbreak has been studied using three different modelling approaches, namely the basic buoyant plume analysis, the computational fluid dynamics analysis and the macroscopic multi-zone modelling approach.

Once exhausted from a seriously contaminated bathroom, the virus-laden moist air flows upwards and is dispersed in the poorly ventilated 1.5 m wide by 6 m deep re-entrant space. The virus-laden buoyant moist air can find its way into bathrooms or living rooms of upper floors due to negative pressure created by exhaust fans or the action of wind flows around the building. A kitchen in the path of the invading polluted moist air may also be contaminated. Buoyant moist and warm air plumes in the re-entrant space is suggested and shown to be responsible for the rapid virus spread in the Amoy Gardens Flats 7 and 8, Block E, where more than 80 SARS cases were confirmed between 21st March and 3rd April 2003.

Two computational fluid dynamics software packages, Fluent and Airpak, are used. Fluent is a three-dimensional general-purpose CFD package for modelling fluid flows. In this application, we have used the basic RNG turbulence model and the Reynolds Stress Model for modelling turbulence. The virus-laden aerosols are believed to evaporate rapidly (within a few seconds in air) and we have only considered the modelling passive scalars. Airpak is also a three-dimensional CFD package for modelling building ventilation flows, but has a limited available turbulence models. A multi-zone air flow model (Li, 1993), MIX, is also used to investigate the virus spread between flats in Block E. Figure 3B shows the virus-laden particle flows simulated by Airpak.

Both the HKSAR Government and the WHO team have suggested a transmission route by the soil drainage system. Most of the infected residents in Amoy Gardens showed diarrhoea symptoms. Our studies have shown that large amounts of aerosols can be generated in the vertical stacks, suggesting that the drainage system served as an amplifier of the virus source. Our studies so far have disproved the hypothesis of transmission through the drainage system.

Our preliminary studies have supported the following four processes of virus spread in the Amoy Gardens outbreak.

1. Amplification of the virus source from 16/F, Flat 7 in Block E: The drainage system generates virus-laden aerosols, which return to the bathroom and then enter the re-entrant by an exhaust fan or other routes;

2. Spread in Flats 7 and 8 in Block E: Buoyant plume in the re-entrant space spreads the virus;

3. Spread to Flats 1-6 by air flows between flats, driven by wind pressures and other natural and mechanical forces;

4. Spread from the Flat 7/8 plume to other blocks due to the northeasterly winds.

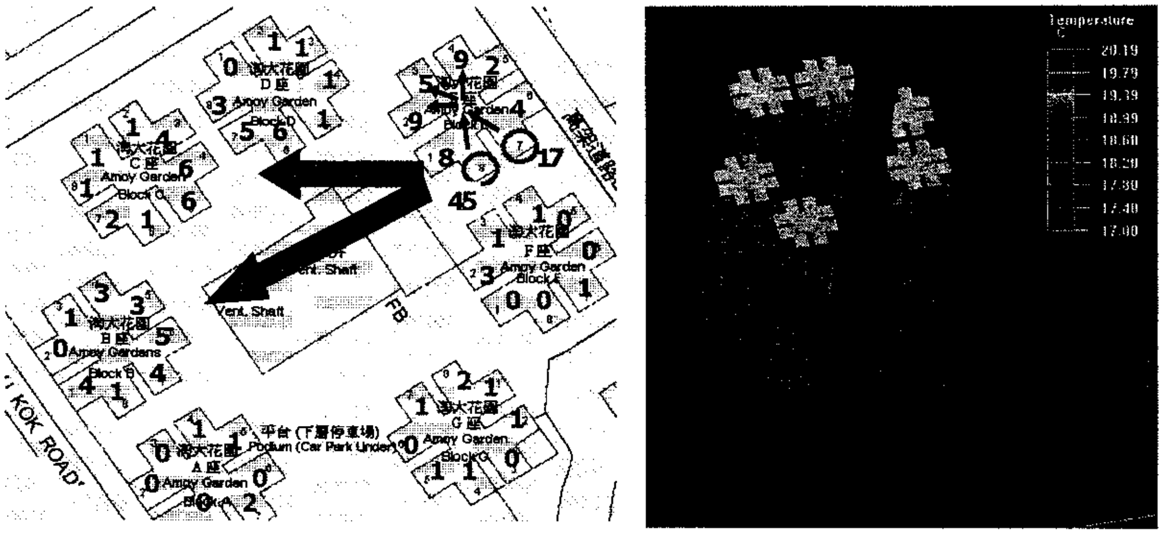


Figure 3. (A) Left: Distribution of the infected flats between 21 March and 3 April in different wings of Blocks A-G. (B) Right: Preliminary CFD simulation of wind flows. A northeasterly wind carries the plume into middle floors of the Block C and D, where were mostly infected in the two blocks.

Our studies on the Amoy Gardens outbreak show the need for improving drainage system design, installation, as well as the need of stricter regulations in terms of maintenance. The typical re-entrance design in Hong Kong high-rise apartment buildings also needs to be further studied.

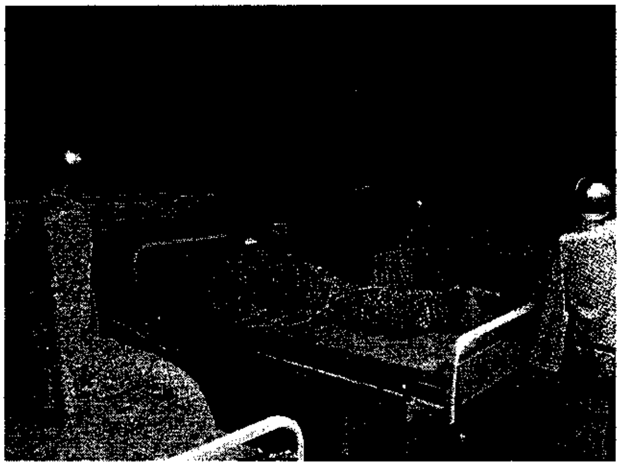
4. EXAMPLE 2 – AIR CONDITIONING SYSTEMS FOR SARS WARDS

The hospital care workers have been the most severely affected professions during the SARS epidemics in Hong Kong elsewhere. More than 20% of the confirmed cases in Hong Kong were health care workers; which occurred in 21 different hospitals, including the teaching hospitals of the two medical faculties in Hong Kong. The effectiveness of the air conditioning system in existing hospital SARS wards has been a great concern since the outbreak. In response to this concern, the Hong Kong Institution of Engineers formed an expert group in early May - the SARS-Busters to investigate and develop an air-conditioning system that is suitable for SARS wards. A new SARS ward air conditioning design was completed in late May (SARS Busters, 2003). The new design is well supported by extensive computational fluid dynamics simulations (SARS Busters, 2003). The main idea of the new design is to minimize air mixing and improve virus removal effectiveness in the SARS wards.

HKU was commissioned by HKIE in late May 2003 to construct a full-scale mock-up test chamber for SARS wards and to investigate the performance of a new air-conditioning system designed by the SARS-Busters. The full-scale test room was completed in less than 4 weeks time between late May and mid June. The air-conditioning system tests were completed in another four weeks time between mid June and mid July 2003.

The full-scale test room constructed in the Building Services Laboratory at the University of Hong Kong is 6.7 m long, 6.7 m wide and 3 m high, which is a typical ward size in Hong Kong. A 0.3 m suspended ceiling is used to accommodate the supply air ducts as well as lighting. A modular approach is adopted for the test room envelope design; see Figure 4A. 1 m by 1 m wall panels and double-glazed windows are used so that the room can be (relatively) easily modified to a different size. Both insulation and double-gazed windows are provided; see Figure 4A. The air conditioning system is designed to be as closely as possible to the new design by the SARS-Busters, equipped with a 9-ton chiller. Both lighting loads and equipment loads are modeled as closely as possible to the real situations as suggested in the SARS-Busters report.

(A) The completed test room, where the modular structure of the envelope can be seen.



(B) Part of the test room showing both sleeping (titled beds) and sitting patients.

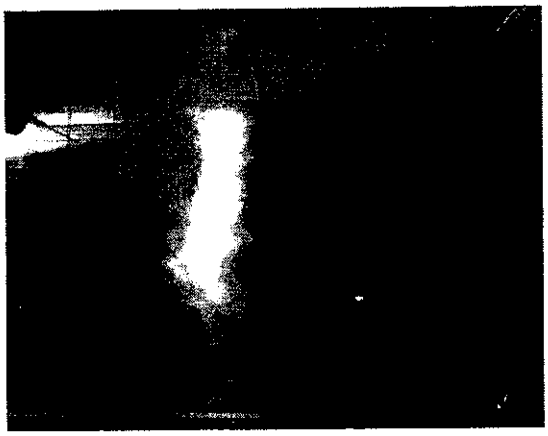
Figure 4. The full-scale test room

A rather unique feature of the full-scale test room is the use of seven identical breathing thermal manikins for modeling both patients and HCWs; see Figure 4B. These clothed manikins are designed to be much simpler than the thermal manikins commonly found in thermal comfort studies. Made of flexible ventilation ducts and a copper hollow sphere, both head and body temperatures are individually controlled. These simple thermal manikins are made to model the effect of thermal airflows due to the heat generation from the patients. The heat dissipation in both head and body parts are designed to follow average adult figures. Some of the manikins are connected to a simple artificial "lung" that provides exhalation through the mouth. Due to time limits, these manikins do not have a nose at this point. Thus, we could only model the mouth expiration flows. Existing studies have shown that mouth exhaled flows are more critical than that through a nose (Bjorn and Nielsen, 2002). Most people use nasal breathing when quiet, but use oral breathing while talking and singing.

In order to test the performance of the proposed new air conditioning systems, we have considered a large number of cases to test the effect of bed-head and below-bed exhaust ratios, door opening, people movement, more middle duct supply etc. Both smoke visualization and aerosol measurement are carried out to provide both qualitative and quantitative indicators.

Figure 5 shows some typical exhaust and supply flow patterns. If the patient's head is more than 100 mm away from the exhaust, the capture efficiency is reduced to zero when the bed-head and below-bed exhaust ratio is 10:90. Using a higher extraction ratio at bed-head level exhaust or using a retractable hood can improve this constraint in the effective capturing distance. At an extraction ratio of 30:70, the critical capturing distance increases to 200 mm. We suggest that a 30:70 exhaust ratio is a suitable option for this test room. It should be noted that this optimum extraction ratio should not be used universally in all situations as the airflows are affected by many other parameters. Either computational fluid dynamics simulations or full-scale tests will be necessary to verify the optimum design parameters for a new design.

(A) Exhaust flow patter with a horizontal distance between the grille and the patient's head of 100 mm



(B) Smoke visualization of supply air streams with a background of both sitting and lying patients.

Figure 5. Smoke visualization of both the exhaust air streams and supply air streams. Extraction ratio is 10:90.

The supply air streams are clearly shown in Figure 5B. Due to the relatively low velocity that is used for supply (less than 0.2 m/s), the supply "jets" may be best described as "negative thermal plumes", which means that the primary supply air flow is dominated by the negative buoyancy force as the supply air is relatively heavier than the surrounding. Thus, it is expected that the cooling load in the room will mostly affect the airflow pattern. If the cooling load is low, then the supply air temperature is high, and there may not be sufficient negative buoyancy force to drive the airflow downwards.

We also measure the aerosol concentrations in all beds to access the possibility of cross-infection in the test room. This is done by placing the aerosol generator in Bed 6 in Figure 6. Measurement of aerosol concentrations is carried out for all other beds and the middle corridor.

Figure 6 summarizes the measured concentrations at various locations in the room when the aerosols are generated near the source patient's mouth in Bed 6. There is a mixing in the source patient side of the test room. All beds in this half of the room have recorded relatively high virus-laden aerosol concentrations. It indicated a difficulty in controlling the unidirectional flows in the test room. On the other hand, the concentrations in the other half of the room are relatively very low, suggesting that the middle ducts play an important role in "separating" the airflow between the two sides of the room as an "air curtain". It should be noted that Beds 1 and 2 recorded a relatively higher dust concentration than Bed 3. This may be due to the use of a cooling fan for the thermal manikin controller, which is located between Bed 1 and Bed 2. The fan is sufficiently strong to cause some local mixing in the region, which might have caused some particles on the beds or the floor to be re-suspended.

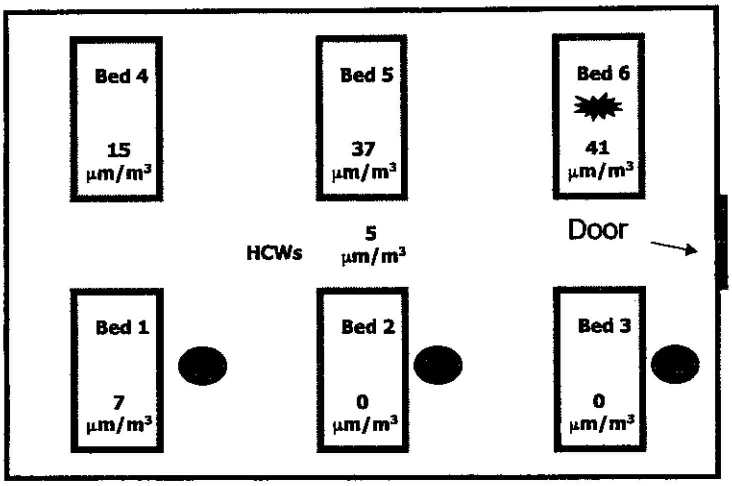
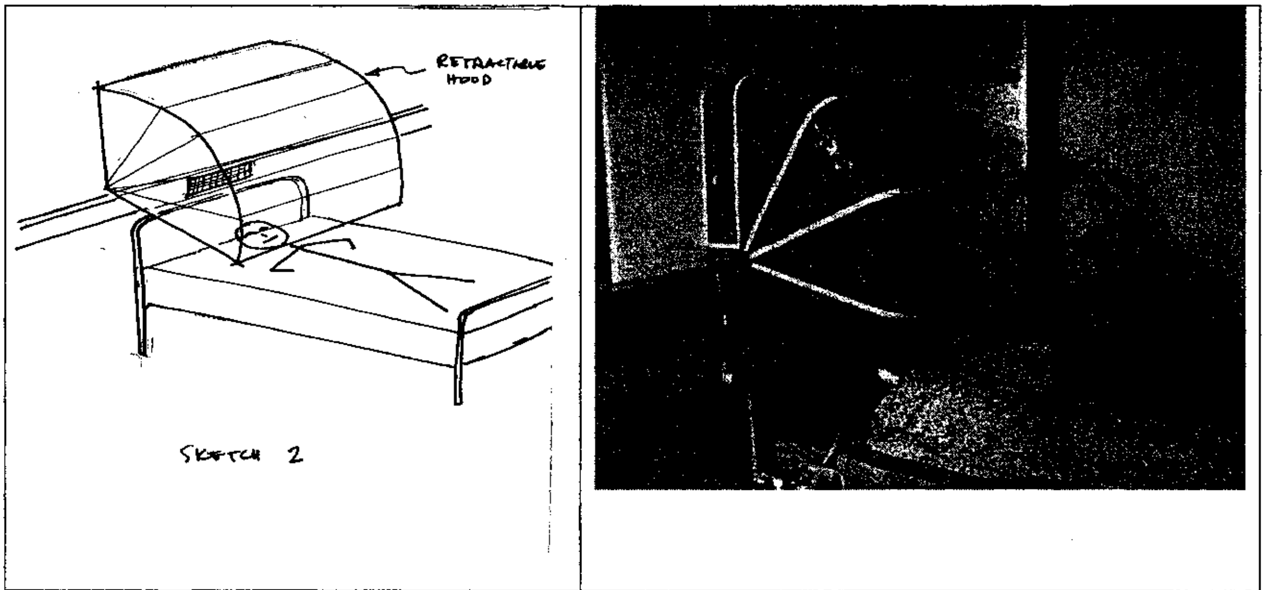


Figure 6. Illustration of the location of source patient, other patients and health care workers (HCWs). Measured mean values of aerosols orginated from the source patient are also shown.

We also considered various source control methods. One example is a local exhaust hood designed by Mr Victor Cheung, a SARS-Buster, when he visited the full-scale test SARS ward. A prototype installation is constructed in our building service laboratory; see Figure 4.



(A) Design drawing by Victor Cheung	(B) A prototype of the retractable hood

Figure 8. Retractable hood design and prototype for bed-head applications in SARS Wards. The hood was first designed by Mr Victor Cheung of JRP, Hong Kong.

The local hood is found to be very effective in removing the virus-laden aerosols. With the hood, the virus-laden aerosols originated from the patient's mouth can be captured fully even when the patient is more than 300 mm away from the exhaust. Obviously, the patient's head should be covered under the hood to obtain the 100% capture efficiency. It is found that the exhaled airflow direction is also an important parameter. If the patient faces outside and the exhaled airflow is directed to the surrounding, the virus-laden aerosols can escape into the test room.

A number of critical comments have also been received from the visiting medical professionals on other aspects related to infection control. For example, the plastic materials used for the prototype hood may not be adequate due to the possible difficulties in surface cleaning. It is recommended that the retractable hood may be built to be light structure, disposable or washable, and can be easily hooked on or off to the wall. The local hood design still needs to be improved with inputs from the medical professions.

5. EXAMPLE 3 - PREDICTING SUPER SPREADING EVENTS

One of the most intriguing characteristics of the 2003 SARS epidemic is the occurrence of super spreading events (SSEs). A super-spreading event refers to a large cluster of infection in which one or more individuals disproportionably infect many more other individuals than an average SARS patient. WHO has explained that the super-spreading phenomenon may be due to the lack of stringent infection control measures in hospitals during the early days of the epidemic, which could not explain some of the identified SSEs so far, e.g. the Amoy Gardens outbreak in Hong Kong. The transmission dynamics of and effective control and preventive measures for SSEs remain unknown.

With a background in modelling non-linear dynamics of airflows in buildings, we have carried out mathematical and statistical analysis to identify the occurrence of SSEs in the Hong Kong and Singapore epidemics using ???. Research in this area is not necessarily related to aerosol transport and control. However, it is important to know when the infection occurs in various SSEs, so that the exact cause can be investigated, and environmental control systems may be one of the reasons.

Our predicted occurrence of SSEs agrees well with the reported occurrence of all seven super spreaders in the two epidemics; see Figure 9 for the Singapore epidemic. Additional unidentified SSEs were also found to exist; see Table 1. SSEs are largely responsible for the outbreaks in Hong Kong and Singapore and there also seems to be "synchronized" occurrence of infection peaks in both the community and hospitals in Hong Kong. We suggest that the daily infection does not correlate with the daily total number of the symptomatic cases, but with the daily number of the symptomatic cases with a long waiting period to hospital admission after the onset of symptoms (Not shown in figures here).

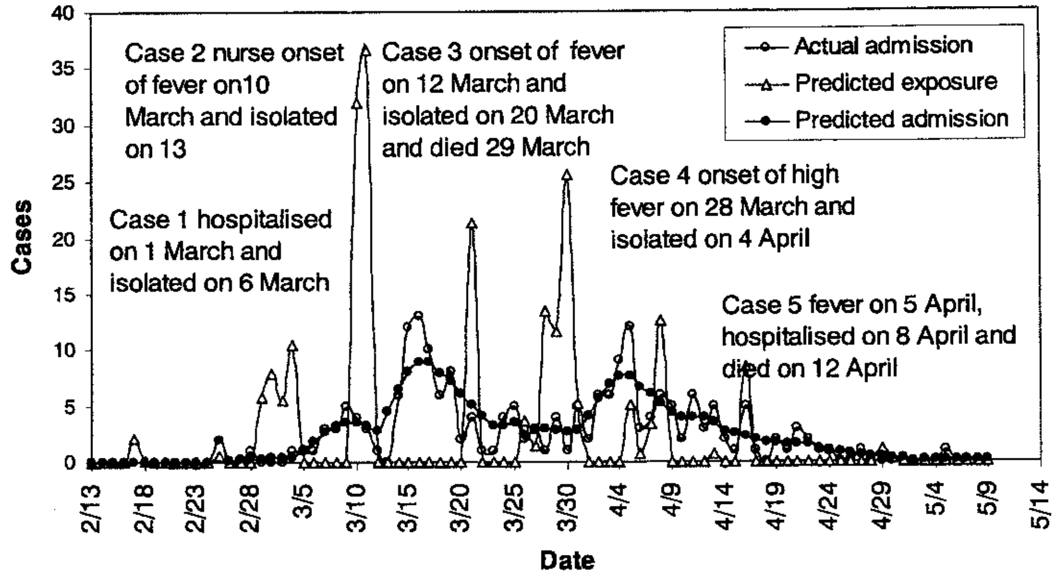


Figure 9. The daily cases of onset of symptoms and the infected in the Singaporean epidemic.

Table 1. Comparisons of predicted and reported numbers of infected due to SSEs in the Singaporean and Hong Kong outbreaks.

	Peaks	Predicted No. of infected	Predicted No. of infected due to SSEs	Reported infected linked to SSEs*
Singapore	1-4 Mar	29	24	21 + 3 [1]
	10-11 Mar	68	66	23 + 5[1]
	21 Mar	21	19	23 + 18[1]
	26-31 Mar	60	52	40 + 22[1]
	5-8 Apr	21	10	15[1]
	16-18 Apr	8	7	Unidentified
Hong Kong	8-11 Mar	276	Not predicted	156 [2]
	19-22 Mar	567	521	329[3]
	31 Mar – 7 Apr	498	267	Unidentified
	11-16 Apr	211	78	Unidentified
	23 Apr – 7 May	116	21	Unidentified

*) A+ B, where A is the reported number of the infected linked to a super spreader and B is the number of the suspected linked to a super spreader. (1) Leo et al, 2003), (2) Tomlinson and Cockram (2003) and (3) HK Government (2003).

6. CONCLUDING REMARKS

Our hypothesis for the virus transmission in the Amoy Gardens outbreak still needs input from field evidences of virus-laden aerosols transmission. Due to the changing weather conditions, collection of relevant data will not be an easy task. Input from epidemiological studies such as case-control studies are also urgently needed. Our environmental investigation has shown a good correlation between the plume and wind flow pattern and the infection pattern. Our work on the SARS ward ventilation is also applicable to other respiratory infectious disease control in hospitals. The full-scale test room study shows the difficulty in controlling airflow pattern in a hospital ward. However, the use of low-velocity cool air supply at the ceiling level offers a possibility of minimizing flow mixing in the room. The SARS ward air conditioning system proposed by HKIE SARS Busters seems to be perform well in the full-scale test ward. The ideas of bed-head level exhaust and the retractable bed-head hood are effective in providing local capture of the virus-laden aerosols. However, input from medical professionals is needed to further improve the system.

Our studies have shown that various building services systems and components have shown to play a big role in the recent SARS epidemics in apartment buildings and hospitals in Hong Kong. The most important building systems include the drainage systems, the building ventilation system as well as related various aspects building design such as use and design of the re-entrance in high-rise apartment buildings. Both building services research and education are important as we consider an integrated building design approach, balancing the construction and operation cost, thermal comfort, indoor air quality, energy efficiency as well as healthy environment.

The unfortunate SARS epidemics have given us all a painful lesson in terms of basic building services design. More than 90% of our time is spent indoors. It is time for both the community and engineering professionals to review the roles of building services engineering in building design. What can we do in order to safeguard our buildings and indoor environment against other new infectious diseases, and also against the potential bio-terror attacks and ultimately to provide a healthy, comfortable and enjoyable indoor environment for us all?

ACKNOWLEDGEMENT

The projects described in this paper have been financially supported by the HKU SARS Fund (Project Amoy), by the Faculty of Engineering, the University of Hong Kong and the Hong Kong Institution of Engineers SARS Fund (Full-scale test ward). Project Amoy is led by Prof. J.H.W. Lee, former Dean of Engineering and we thank him for leading us into this exciting research topic. Installation, testing and commissioning of the air conditioning system for the mock-up room are coordinated and carried out by Ir Victor Law of Atal Engineering. We also like to thank Ir Victor Cheung, Convener of the SARS-Busters' mock-up study and all SARS-Busters. We also wish to thank all donors and supporters during the all phases of the project. Mr Leung Wing Kam acted as the lab coordinator for the SARS ward project. He also designed and constructed seven breathing thermal manikins. Mr Qian Hua conducted all the measurements for SARS ward testing. Leung Mr Kwan Siu Wah, Ms Shuangping Duan, Mr Jerry Chan and Mr Albert Lee from HKU actively participated in the SARS ward project.

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室内环境中含 SARS 病毒颗粒的传播和控制 —传播路径及病房通风

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摘要：2002 年 11 月到 2003 年 6 月间在香港等地发生的严重急性呼吸系统综合症（SARS）留给我们一个还没有回答的问题一在一些 SARS 超级传播事件中，病毒是否借助于空气传播？在流行病学回答这个问题以前，在处理 SARS 病房的空调通风设计这类环境控制、测量等问题时，我们必须假定存在空气传播的可能性。针对淘大花园及威尔斯亲王医院 8A 病房中 SARS 爆发的流行病学研究表明：直到我们写这篇文章的时候（2003 年 8 月），还不能排除空气传播的可能性。

病人通过咳嗽、喷嚏、呼吸可以产生大量含 SARS 的悬浮颗粒或液滴，另外甚至在病人的排便、排尿过程中，由于雾化作用，也可产生含 SARS 的颗粒。如不考虑含 SARS 悬浮颗粒的传染性，就可以通过分析及试验等方法研究颗粒在室内外的扩散、蒸发规律。由于粒径在 0.5 到 10μm 之间，悬浮颗粒很容易随着气流运动，也可长时间悬浮在空气中。这些特性对病毒的传播路径及建筑物（尤其是病房）的空调通风系统设计具有重要的意义。

作为流体力学、大气污染和流行病学的专家组成员，我们参加了淘大花园 SARS 爆发的病毒传播路径研究。在 2003 年 3 月 19 日左右的 SARS 爆发中，有超过 300 人被感染。基于理论、数值模拟及试验等方面的研究，本文提出了一个关于淘大花园 E 座第 7、8 单位、E 座其余单位、该建筑群中其余建筑物中 SARS 传播路径的一个合理假说。2003 年 5 月底，香港大学也受香港工程师协会委托建造了一个 SARS 病房的全尺寸模型， 并研究了一新设计空调系统的性能。由于采用了模块化设计，新设计病房也可用于模拟其他类型的病房，例如：深切治疗部（ICU）、发热病房和 SARS 单人病房，等。该全尺寸模型房从 5 月下旬开始建，于 6 月中旬建成，用时不到 4 个星期。从 6 月下旬开始进行空调系统性能测试，到 7 月中旬完成，用时也不到 4 个星期。新设计空调系统在这个几乎真实的 SARS 模拟病房中运行性能良好。

关键字：传播路径　悬浮颗粒扩散　SARS 病房　病房通风　局部回风　测试房

Dispersion and control of SARS virus aerosols in indoor environment – transmission routes and ward ventilation

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Abstract: The severe acute respiratory syndrome (SARS) epidemics in Hong Kong and elsewhere between November 2002 and June 2003 have left us an unanswered question – were the SARS virus transmission airborne in some of the super spreading events? Before the epidemiological answer to this question becomes available, it is important that we consider the possibility of airborne transmission when dealing with environmental control measures such as air conditioning and ventilation design in SARS wards. Epidemiological studies on the Amoy Gardens outbreak and the 8A ward outbreak in the Prince of Wales Hospital have shown that the airborne transmission cannot be ruled out at the time of writing this paper (i.e. August 2003).

SARS virus-laden aerosols and/or droplets can be originated from coughing, sneezing and breathing of a patient, or even produced by an aerosolizing process with input of faeces or urine of a patient. Not taking into account of the infectivity of the virus-laden aerosols, the dispersion and evaporation of aerosols in and around buildings can be analyzed and experimentally studied. With

sizes of between 0.5 and 10 μm in diameter, the aerosol particles can easily drift in an airflow current and stay in air for a long time. This has significant implication to transmission routes of the virus as well as air conditioning and ventilation system design in buildings, in particular in hospitals.
Working in a team of experts with a background in fluid dynamics, air pollution, and epidemiologists, we have participated in the Faculty of Engineering's research team in investigating the transmission routes in the Amoy Gardens outbreak, where more than 300 people were infected around 19 March 2003. Based on theoretical, computational and experimental studies, a plausible hypothesis has been proposed on the transmission routes for Flats 7 and 8 in Block E, other flats in Block E and other blocks in the Amoy Gardens. HKU was also commissioned by the Hong Kong Institution of Engineers (HKIE) in late May 2003 to construct a full-scale mock-up test chamber for SARS wards and to investigate the performance of a new air-conditioning system designed by SARS-Busters. Adopting a modular design, the new full-scale test room can also be used for testing other types of hospital rooms such as intensive care units (ICUs), fever wards and single-occupancy SARS wards etc. The full-scale test room was completed in less than 4 weeks time between late May and mid-June. The air-conditioning system tests were completed in another four weeks time between mid-June and mid-July 2003. The new air conditioning system is found to perform well for a nearly realistic full-scale SARS ward.
Keywords: Transmission routes　aerosol dispersion　SARS wards　hospital ventilation　local exhaust　test room

0 前言

作为 21 世纪出现的第一个严重传染病，严重急性呼吸系统综合症（SARS）在 2002 年 11 月到2003年6月间的流行导致一场由国际卫生组织（WHO）领导的、空前的国际合作。在全球 34 个国家和/或地区，总共报告了 8422 个可能案例，其中916人死亡[1]。到7月5日，WHO 宣布，SARS 的传播已被控制。

SARS 由一访问广东被感染的医生传播到香港及其余各地，该医生在一个宾馆里至少感染了 14 个来自于香港、加拿大、越南及新加坡等地的客人。可能由于起初不熟悉 SARS 病症，大多数最初感染者在医院里都引起了较大的传染。3 月 15 日，WHO 发布了空前的旅游警告。SARS 的流行对香港及其余各地的经济及卫生保健系统产生了深远影响，

Peiris 等[2]首先确认了冠状病毒是引起严重急性呼吸系统综合症的病因。SARS 病毒是一种神秘的、易传染的病毒。相信 SARS 病毒主要通过近距离接触传播，尤其是接触了病人的呼吸系统分泌物。被 SARS 病人排出的呼吸系统分泌物及其他排泄物（如：唾液、眼泪、尿、粪）污染的物体可能在病毒的传播中也具有一定作用[3]。Tsang [3] 提出，通过排泄物传播 SARS 的情况是较少见的，但在一定环境条件下，这种方式的传播可以引起大规模的 SARS 爆发。

在 2003 年的 SARS 流行中，一个最令人感兴趣的特点是存在超级传播事例（SSEs）。一个超级传播事例是指一个或几个 SARS 病人感染了一大群人，且感染人数远远超过每个 SARS 病人的平均感染人数。WHO[4]认为超级传播现象的存在是由于在 SARS 流行的早期，医院中缺乏严格的预防传染措施。但这不能解释迄今发生的所有超级传播现象，如香港淘大花园的 SARS 爆发。

在一些超级传播事件中，研究显示，建造物周围的环境系统对 SARS 病毒的传播起了重要作用。在 SARS 传染期间，媒体对香港医院中空调系统性能不良、公寓建筑的污水系统问题、如何改进医院空调系统和对病毒源进行控制等作了大量报道。这反映了政府、公众及医院护理人员对这些问题的共同关心。

本文讨论含 SARS 病毒的悬浮颗粒在室内的传播规律及相应控制方法。我们将给出自香港 SARS 爆发以来香港大学机械工程系在这些方面所开展的研究实例。主要涉及大规模爆发中 SARS 的传播路径、如何改进建筑设计、超级传播者的传播动力学、SARS 病房空调、进行病毒源控制的局部回风等。其中许多工作仍在进行中，这里仅列出初步的结果。

1 含 SARS 病毒悬浮颗粒的传播特性

Barker 等[5]对传染性呼吸系统疾病在公共及家庭建筑中的传播路径研究进行了综述，Mendell 等[6]对工作空间(如办公室)中的传播路径研究进行了综述，Cole 和 Cook[7]则对卫生保健场所中的病毒传播路径研究进行了综述。其他一些呼吸系统病毒，如引起感冒和流感的病毒，可通过吸入带病毒悬浮颗粒、手与病毒的接触（包括与病人握手、接触污染表面）而感染。大多数呼吸系统病毒的空气传播研究都不能最终确定为人一人方式传播，或人一物一人方式传播。

由于 SARS 病毒是一种新的冠状病毒，关于 SARS 如何传播的完整图象还不清楚。WHO 合作研究室网络中的科学家证实，SARS 病毒可以在烘

干的塑料表面上存活 48 小时，在粪便中至少存活 2 天，在尿中至少存活 24 小时。腹泻的 SARS 病人粪便中的酸性较低，SARS 病毒可以存活达 4 天。

尽管较为困难，含 SARS 悬浮颗粒在室内的传播是可以分析和预测的[8]。喷嚏、咳嗽和说话产生的颗粒的核心大小与所含病毒的种类、产生过程和环境条件等有关。喷嚏可以产生大约 100 万个直径达 100μm 的液滴，另有几千个主要由唾液组成的较大液滴。液滴产生以后，开始蒸发，质量和尺寸都减小，当颗粒足够小时(0.5～12 μm)，可以经由空气传播。因此，即使较大的液滴最初由于重力作用而沉降，随着蒸发进行，尺寸减小，这些颗粒也可能再次悬浮。人体产生液滴的尺寸分布也决定于呼出时的气流速度、流体粘度、及出流的流道（即鼻子、嘴或两者都有）。由于热舒适的需要，空调房间内的气流速度一般为 0.25 m/s，而液滴的沉降速度非常低，一般为 0.2～1.2m/h（即 0.05～0.3 mm/s）。空调房间内的平均气流速度一般设计为小于 0.25 m/s。在送风格栅处的典型送风速度为 2～4 m/s。由于液滴的尺寸很小，液滴的运动主要决定于空气的紊流流动。

Brundrett[9]发现液滴的蒸发速率决定于环境湿度。液滴的蒸发是颗粒动力学中的一个基本过程，对大气悬浮颗粒研究、云的微观物理学、核反应堆安全、燃烧和雾化（Beck 和 Watkins[10]）等都非常重要。液滴蒸发同时涉及液滴和周围气体的热、质和动量传递。动量传递决定颗粒的运动，质量传递决定液滴的尺寸变化，热量传递引起液滴的温度变化。由于空调房间内空气的相对湿度一般控制在 50～60%，当液滴释放到空气中以后，其尺寸将急剧减小，如图 1 所示。

含固体小颗粒的液滴（如含 SARS 的颗粒）的蒸发包括 2 个阶段，即，快速蒸发阶段和固一液达到临界质量比后的临界蒸发阶段，在快速蒸发阶段，液滴质量和直径都持续减小。所谓临界质量比状态，就是液滴中离散的不溶固体颗粒收缩聚集形成团块状（不能继续收缩），同时固体颗粒间的空穴中仍充满液体。在临界蒸发阶段，蒸发速率不大。在经过第二阶段后，液滴可能碎裂，即，其中所含的固体颗粒相互分裂(Elperin 和 Krasovitov[11])。遗憾的是，目前对于咳嗽、喷嚏及呼吸过程产生液滴的蒸发过程还没有系统研究。

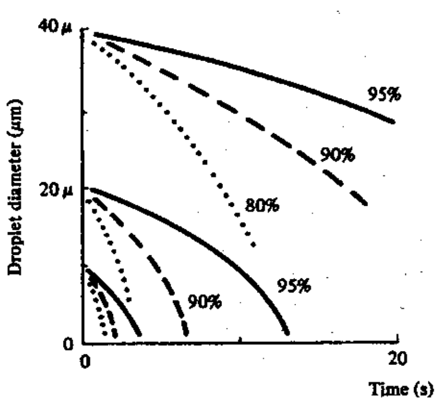
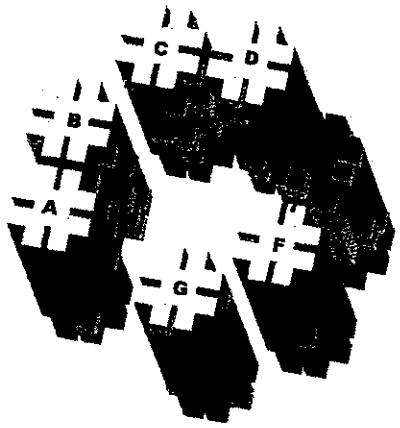


图 1　在不同环境的相对湿度下液滴尺寸的变化 (Brundrett [9])

2　实例 1－淘大花园 SARS 的传播路径

在 2003 年 3 月 21 日到 4 月 1 日间，香港淘大花园有超过 200 居民感染了 SARS。被感染的案例并不是随机分布的，大多数案例发生于某几幢建筑及其某些楼层，明显地具有一定规律，见图 2。淘大花园 SARS 爆发不久，香港政府及世界卫生组织都对可能的病毒源头和传播路径进行了研究。尽管研究认为存在几种可能的路径，但都不能完全解释被感染者的分布特征。研究结果证实 SARS 病毒源主要来自于建筑污水管的聚水器，同时揭示被感染者的分布特征与天井中的空气流动、E 座各单位间的气流流动及各幢建筑间的风向强烈相关。



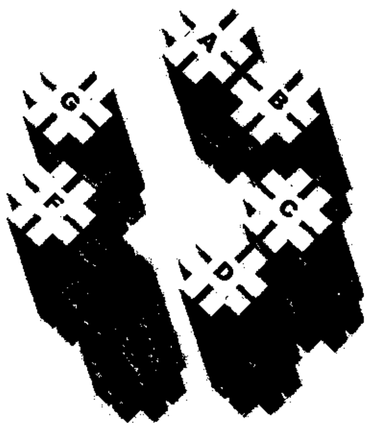


图2　在3月21日到4月3日间淘大花园被SARS感染的单位分布。每幢楼有8个单位，E座的第7、8单位感染个案最多。该座的1～4单位感染个案数其次，而第5、6单位感染个案最少。B、C、D座的感染个案比较集中。其余建筑的感染个案很少。

2003年4月17日香港政府[12]第一次发布了其主要发现，认为环境因素在SARS爆发中起了重要作用。大多数淘大花园的病人都有腹泻，导致大量SARS病毒被排到E座(即感染最严重的建筑)的污水管中。源头病人首先感染了E座的一批居民，然后通过E座的污水系统、人与人的接触及大厦公共设施(如升降机及楼梯)，令大厦内的一批居民感染病毒。这些受感染的居民其后可能通过人与人的接触及受污染的环境设施把病毒再传播给E座内外的居民。经过3个星期的研究，WHO[13]推测，含SARS的液滴从污水管回流到浴室内，然后通过浴室的抽气扇再排放到各单位间的天井中，最后这些带病毒的滴液通过窗户进入了较高的楼层单元。Peiris等[14]研究了淘大花园SARS爆发中被感染的75个病人，发现病人家卫生间厕盆内有SARS病毒，认为存在口一排泄物间传播的可能性。Donnelly等[15]也对淘大花园SARS爆发的可能原因进行了探讨。

此次事件的源头病人被认为是一个超级传播者，他分别于2003年3月14日和19日到过淘大花园E座的一个单位。我们研究显示他的第二次到访日期与SARS预测发病日期一致。到4月1日，超过200位淘大花园E座居民被隔离在假日营地。

我们基于多学科交叉，综合悬浮颗粒动力学、热流体力学、建筑机械工程等多个学科，采用理论分析、试验研究及计算机模拟相结合的方法，研究了淘大花园的SARS传播途径。采用全尺寸实验室模型，详细研究了污水排放系统；基于实验室模拟及现场测量，研究了悬浮颗粒的产生过程；并进行了数值模拟。精确模拟空气流动及含病毒颗粒的扩散是困难的，当涉及复杂建筑物时尤其如此。采用3种不同的模拟方法，研究了淘大花园SARS爆发中含病毒颗粒的传播过程，即，基本的热羽流分析、计算流体力学分析、多区空气流动模拟。

当含SARS病毒的湿空气从一被严重污染的浴室排到天井中后（宽1.5m，深6m，通风条件很差），湿空气将上升并散布于天井。由于浴室排气扇或风所引起的负压影响，含病毒湿空气将上升进入大厦上层居民家的浴室和客厅。位于湿空气进入通道上的厨房也将被污染。可以推测，天井中浮力驱动的湿、热羽流是造成淘大花园E座第7、8单位SARS快速传播的原因。在2003年3月21日到4月3日间，这两个单位中有超过80人被确诊感染SARS。

数值模拟基于两种计算流体力学软件，即，Fluent和Airpak。Fluent是一个通用的三维CFD软件。为模拟紊流流动，采用了重整化群（RNG）紊流模型和Reynolds应力模型。由于含病毒的液滴蒸发非常迅速（几秒时间），采用了示踪标量法近似模拟污染物的扩散。Airpak同样也是一个模拟建筑通风的三维CFD软件。另外，各房间内的病毒传播规律采用多区空气流动模型(Li[16])—MIX，进行模拟。图3b表示用Airpak模拟得到的含病毒颗粒在E座天井中的流动状况。

香港特区政府和WHO研究小组都认为存在通过污水系统传播病毒的可能。淘大花园大多数感染者都患有腹泻。研究显示，垂直的污水管聚水渠中可产生大量的悬浮颗粒，暗示污水系统起病毒源放大器的作用。迄今我们的研究结果否定SARS通过污水系统传播。

我们初步的研究结果显示，淘大花园SARS爆发中存在以下4个病毒传播过程：

1. 位于E座16层的一个单元（即源头病人所住的单元）将病毒源放大：污水系统产生大量的含病毒悬浮颗粒，颗粒返回浴室，然后通过排气扇或其他途径再进入天井；
2. SARS在E座的第7、8单位传播：病毒通过浮力驱动的热羽流在天井中传播；
3. 在风压和其他自然及机械力的驱动下，病毒通过各单位间的空气流动传到E座的1～6单位；
4. 在当时东南风的作用下，病毒从E座的7/8单位传播到淘大花园的其他幢建筑。

研究表明，必须改进淘大花园污水系统的设计及安装，必须采用更严格的日常维护规章。香港典型的高层建筑中天井的设计也需进一步研究。

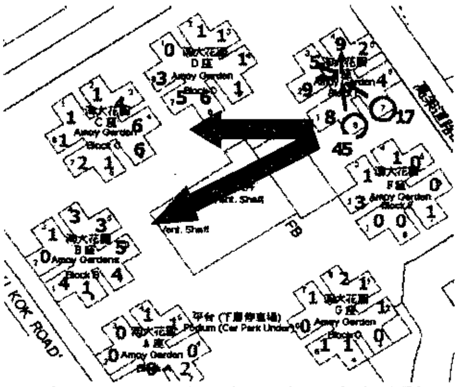


图 3(A) 在 3 月 21 日到 4 月 3 日间，淘大花园 A～G 座被感染的单位分布；

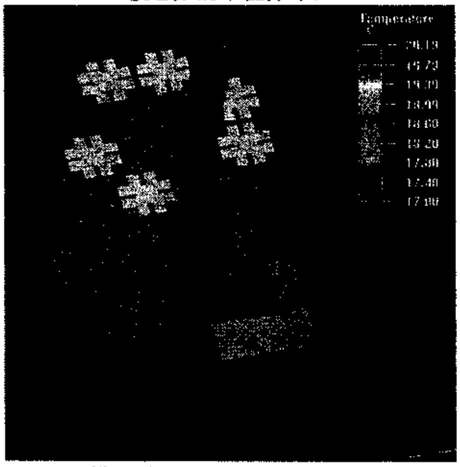


图 3(B) CFD 模拟结果：东南风将 E 座天井中的热羽流传到 C、D 座的中间层，这里集中了 C、D 座最多的感染者.

3 实例 2 – 用于 SARS 病房的空调系统

在香港 SARS 流行中，医院护工受感染情况最严重，占香港确证个案的 20%以上。被感染的护工分布于 21 个不同医院，包括 2 个教学医院。引起公众对 SARS 病房中空调系统性能的严重关注。由此，在 5 月上旬，香港工程师协会组成了一个专家小组，称为 SARS 特工队，以进行适合 SARS 病房使用的空调系统的研究及开发。5 月下旬完成了 SARS 病房用新空调系统的设计[17]。新设计得到计算流体力学仿真结果的支持[17]。设计的主要思想是减少 SARS 病房的空气混合及提高病毒的去除效率。

香港大学受香港工程师协会委托，于 2003 年 5 月下旬建造了一个全尺寸的 SARS 模拟病房实验室，并在其中研究由 SARS 特工队所设计的新空调系统的性能。该全尺寸模拟病房于 5 月下旬到 6 月中旬间完成，用时不到 4 个星期。新空调系统的测试也于 6 月中旬到 7 月中旬间完成，用时也不到 4 个星期。

建于香港大学建筑设备实验室的全尺寸模拟病房长 6.7m，宽 6.7m，高 3m，在香港医院病房中具有典型性。采用 0.3m 高的吊顶安装送风管道及日光灯。模拟病房采用模块化设计方法建造，见图 4A。墙面采用 1m×1m 的面板和双层玻璃拼装而成，可以较为容易的改变尺寸。墙面采用了绝热措施。模拟病房的建造尽量符合 SARS 特工队的原设计。制冷机容量为 9 冷吨。使用的灯光及设备负荷也尽量接近 SARS 特工队的建议值。

(A) 模拟病房，墙面采用模块化设计

(B) 病房内部，可见睡、坐着的模拟人

图 4 全尺寸模拟病房

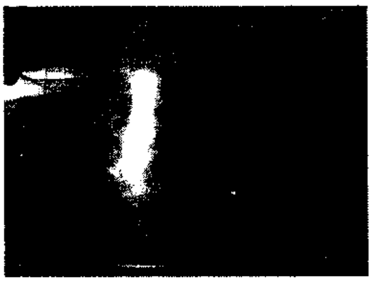
模拟病房的一个显著特点是以 7 个完全相同的假人模拟病人及护工，见图 4B。与一般热舒适性研究中采用的假人相比，我们的假人模型进行了相当简化。假人由柔韧的通风管道和中空的铜球制造，假人头部和身体的温度可以独立控制。制造假人的目的是模拟真实病人的产热对气流场的影响。因此，假人头部及身体的产热率符合真实人体的平均产热率。其中的一些假人与一简单的人工“肺”相连接，以模拟人体的呼气效应。由于时间关系，并没有给假人安装鼻子。所以仅能模拟通过嘴的呼气过程。已有研究认为，通过嘴的呼气过程远比通过鼻子的呼气过程重要[18]。大多数人在安静状态下用鼻子呼吸，但在说话及唱歌时用嘴进行呼吸。

为了测试新空调系统的性能，进行了大量试验以研究头部及床下回风口回风比、开门、人员走动、以及位于两排床中间的送风管送风量等的影响。用烟雾可视化及通过颗粒浓度测量以进行定性及定量研究。

图 5 显示典型的回风及送风流态。当头部回风口和床下回风口的回风流量比为 10：90 时，如果病人头部离头部回风口的距离超过 100mm，头部回风口对病人呼气的捕获效率就接近于零。采用较高的头部回风口回风比或采用可伸缩的回风罩可以增加有效捕获距离。当头部回风口和床下

回风口的回风流量比为 30:70 时，头部回风口对病人呼气的临界捕获距离增加到 200 mm。建议对该模拟病房的头部回风口及床下回风口采用 30:70 的回风流量比。由于室内气流受多种因素影响，该流量比并不是普遍适用的。对其他情况，最佳流量比必须由数值模拟或试验方法确定。

(A) 病人头部距回风格栅 100 mm 时的回风流态



(B) 中间送风口的送风可视化

图 5 回风及送风的烟雾可视化 回风流量比为 10:90

图 5B 清晰显示了送风流态。由于采用了相对较低的送风速度（小于 0.2 m/s），可用"负浮力流"恰当地描述送风"射流"，即，由于送风相对比周围空气重，送风主流受负浮力控制。因此，可以预期，室内冷负荷对气流流型有重要影响。如果冷负荷较低，则送风温度较高，可能就没有足够的负浮力驱动送风向下流动。

通过对病房中各床颗粒浓度分布的测量研究了病房内各床间的交互传染性。见图 6，颗粒发生器位于床 6 病人（假设为源头病人）的嘴部附近。图 6 表示试验测得的各床病人嘴部附近及走廊位置的颗粒浓度分布。可见，在源头病人所处的一侧，存在一定的气流混合现象：这侧各床上测得的颗粒浓度都较高。这也表明，要在病房内对单向气流流动进行控制是比较困难的。但是，病房另一侧各床测得的颗粒浓度相对很低。表明，中间一排送风口形成的风幕对隔离病房两侧的气流起了重要作用。由图 6 可见，与床 3 相比，床 1 测得了相对较高的颗粒浓度。这可能是受试验中使用的一冷却风扇的影响。该风扇位于床 1、2 间，目的是对加热假人的功率控制器进行控制。 该风扇可能使气流发生局部混合，引起床上及地板上的部分沉降颗粒重新悬浮。

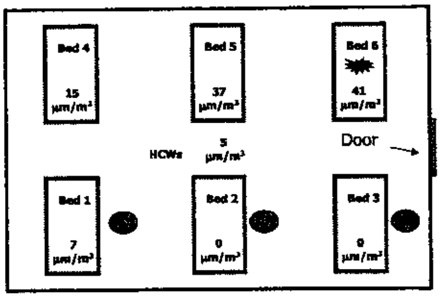
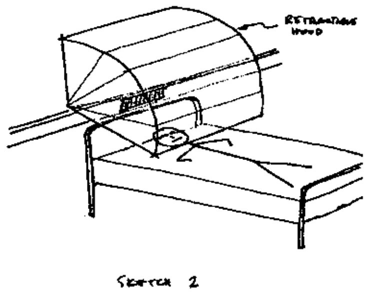


图 6 模拟病房内源头病人、其余病人及护工的相对位置图 同时显示各处的平均颗粒浓度试验值

本文也进行了病毒的源头控制方法研究。一种方法是采用局部抽气回风罩，该回风罩由作为 SARS 破坏者之一的 Victor Cheung 设计。图 6 显示了模拟病房使用的局部抽气回风罩的装置原型。



(A) Victor Cheung 的设计草图

(B) 可伸缩的回风罩原型

图 7 SARS 病房用可伸缩的抽气回风罩的设计图及装置原型，由 Victor Cheung 设计

研究表明，采用局部抽气罩对去除含 SARS 颗粒非常有效。在回风罩作用下，即使病人头部距离头部回风口 300mm，头部回风口也可完全捕获从病人嘴里产生的颗粒。显然，病人头部应完全处于回风罩下，以保证 100%的捕获效率。研究发现，病人呼出气流的方向也是重要影响参数。如果病人沿水平方向呼出气流，含病毒颗粒就可能逃出抽气罩。

在病毒源控制方面，我们与医学专家也进行

了交流，获得了大量重要建议。例如，由于可能存在清洁表面的困难，制造原型抽气罩采用的塑料可能是不合适的。可伸缩的回风罩应亲便、易处理或清洗，并易收、放。在局部抽气回风罩的设计方面，还需根据医学专家的意见进行进一步改进。

4 实例 3 – 超级传播事件的预测

在 2003 年发生的 SARS 流行中，一个重要特点是存在超级传播事例(SSEs)。一个超级传播事例是指一个或几个 SARS 病人感染了一大群人，且感染人数远远超过一个 SARS 病人平均的感染人数。WHO[4]认为，超级传播现象的存在是由于在 SARS 流行的早期，医院中缺乏严格的预防传染措施。但这不能解释迄今发生的所有超级传播现象，如，香港淘大花园的 SARS 爆发。目前对于超级传播事件的传播动力学及其有效控制和预防还处于未知状态。

以室内空气流动的非线形动力学模拟为背景，采用数学及统计学方法，对香港及新加坡 SARS 流行中可能存在的超级传播事例进行了研究。尽管这对于颗粒的传播控制研究显得不重要，然而，知道超级传播何时发生是有意义的，可以对确切的爆发原因进行研究，从而对环境系统进行更好地控制。

对香港和新加坡发生的 SARS 超级传播事例的预测结果与两地的报道数据吻合很好，两地共发生 7 例超级传播事例。图 7 表示新加坡逐日的 SARS 感染者分布。另外还有一些未经确认的超级传播事例，列于表 1。超级传播事例对香港和新加坡的 SARS 爆发有重要责任。在香港，社区及医院出现感染高峰的时间几乎是同步的。我们认为每日的感染数与每日的出现症状数是不同的，有症状的病人在症状出现到被医院收治间还需经一个较长的等待期 (图 8 中没有显示有症状数的分布)。

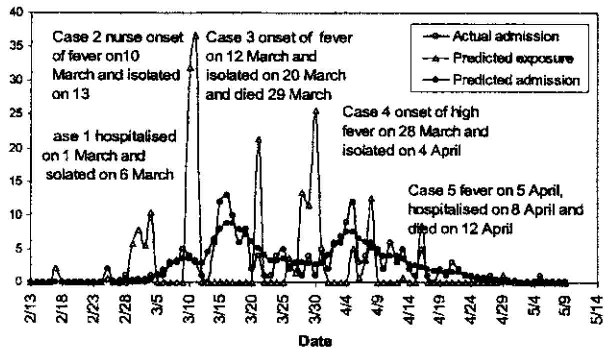


图 8 新加坡 SARS 爆发期间的每日新增病人

表 1 香港及新加坡 SARS 爆发期间超级传播事例中感染人数的预测值和报道值的对比

	爆发时间	预测感染数	预测的由超级传播者引起的感染数	报道的由超级传播者引起的感染数*
新加坡	3 月 1 日～4 日	29	24	21 + 3[1]
	3 月 10 日～11 日	68	66	23 + 5[1]
	3 月 21 日	21	19	23 + 18[1]
	3 月 26 日～31 日	60	52	40 + 22[1]
	4 月 5 日～8 日	21	10	15[1]
	4 月 16 日～18 日	8	7	——
香港	3 月 8 日～11 日	276	——	156[2]
	3 月 19 日～22 日	567	521	329[3]
	3 月 31 日～4 月 7 日	498	267	——
	4 月 11 日～16 日	211	78	——
	4 月 23 日～5 月 7 日	116	21	——

*) A+ B, 其中 A 为报道的超级传播者的传染人数，B 为另外的与超级传播者有关的怀疑感染人数。(1) Leo 等[19]，(2) Tomlinson 和 Cockram[20]， (3) 香港政府[20]

5 结论

本文关于淘大花园 SARS 爆发中病毒的传播过程假设还需含病毒颗粒物传播的试验数据的进一步验证。由于天气条件的不断变化，给收集相关试验数据带来了困难。需尽快开展病毒源控制等流行病学方面的研究。对于淘大花园周围环境的研究表明，天井中的热羽流及当时风向和淘大花园感染者的分布形态有明显的关系。本文关于 SARS 病房通风的研究成果也可用于医院对其他呼吸系统传染病的控制。对全尺寸模拟病房的研究表明，对病房中的气流流型进行控制是困难的。然而，采用天花板低速送风为减少室内气流混合提供了可能性。由香港工程师协会的 SARS 破坏者提出的新空调系统在模拟病房中运行性能良好。采用床头回风口回风和伸缩性回风罩可有效地对含病毒颗粒进行局部捕获。对于新空调系统，还需进一步根据医学专家的意见进行改良。

研究表明，楼宇建筑系统及设备对香港居民建筑及医院中的 SARS 爆发起了重要作用。重要的建筑系统及设备包括大楼的污水排放系统、通风系统、以及有关的建筑设计，如：高层建筑中天井的使用及设计。楼宇设备的研究及训练是非常重要的，尤其表现在建筑的整体化设计，系统建造和运行成本、热舒适、室内空气品质、能源效率以及健康室内环境的综合平衡等方面。

在楼宇设备的基本设计方面，不幸的 SARS 爆发给了我们深刻教训。由于我们 90%的时间都

是在室内度过的，现在到了社会及工程界重新考虑楼宇设备工程在整个建筑设计中的定位的时候了。我们需要考虑，在保护我们的建筑及室内环境免受其他新传染病和可能的生物恐怖袭击的危害方面，以及最终为我们提供一个健康、舒适和愉快的室内环境方面，我们可以做什么?

致谢

本文工作得到了香港大学 SARS 基金（淘大项目)、机械工程系、香港大学和香港工程师协会 SARS 基金 (全尺寸 SARS 模拟病房项目)的支持。香港大学工程学院前院长 J.H.W. Lee 教授领导了淘大项目，感谢他引我们进入这一激动人心的研究领域。由 Ir Victor Law 协调及完成了模拟病房中空调系统的安装、测试和运行。也要感谢模拟病房项目的 SARS 特工队召集人 Ir Victor Cheung 及所有 SARS 特工队。在这里也对项目进行各阶段中给予捐赠及支持的所有人表示感谢。Leung Wing Kam 先生作为 SARS 模拟病房项目的实验室协调人，设计并制造了 7 个呼吸假人。Qian Hua 先生进行了 SARS 模拟病房的测量工作。香港大学的 Kwan Siu Wah 先生、Shuangping Duan 女士、Jerry Chan 先生和 Albert Lee 先生也都参加了 SARS 病房项目，在此表示感谢。作者们特别感谢 Huang Xinghua 博士将本文翻译成中文。

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A FULL-SCALE MOCK-UP STUDY OF SARS BUSTERS' NEW AIR-CONDITIONING SYSTEM FOR SARS WARDS

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ABSTRACT

The University of Hong Kong was commissioned by HKIE in late May 2003 to construct a full-scale mock-up test chamber for severe acute respiratory syndrome (SARS) wards and to investigate the performance of a new air-conditioning system designed by SARS-Busters. The new system designed is found to perform well for a nearly realistic full-scale SARS ward. The new bed-head exhaust design allows some degree of local capture of the virus-laden aerosols originated from a patient's mouth. A 30 to 70 ratio between the bed-head level and below-bed extraction is found to be suitable. The simple and innovative retractable hood design further improves ventilation performance. People movement and opening the test room door are found to introduce significant mixing in the test ward.

Airflow patterns are also found to be very sensitive to minor changes in supply grille design details such as the internal deflector and air distributor, and various supply air parameters such as the velocity, temperature and direction. Air distribution is shown to be a complicated turbulent process and proper design is very necessary for minimizing cross-infection between patients; and between patients and health care workers (HCWs); and for efficient and effective dilution and removal of virus-lade aerosols. The new full-scale test room is designed with some degree of flexibility, which can also be used for testing other hospital rooms such as intensive care units (ICUs), fever wards and single occupancy SARS wards etc.

Key words: SARS wards, hospital ventilation, breathing flows, local exhaust, concentration, test room.

1. INTRODUCTION

As of 7 August 2003, severe acute respiratory syndrome (SARS) has been reported in 34 countries and regions with 8422 reported probable cases and 916 deaths (WHO, 2003). The hospital care workers (HCWs) have been the most severely affected professions during the SARS epidemics in Hong Kong and elsewhere between November 2002 and June 2003. 20% of the infected were HCWs worldwide. 22% of the confirmed cases in Hong Kong were HCWs; which occurred in 21 different hospitals, including the teaching hospitals of the two

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medical faculties in Hong Kong. For example, the first wave of the outbreak in Hong Kong occurred at the Prince Wales Hospital in Hong Kong with a reported super spreader and from March 11 to March 25, a total of 156 patients were hospitalized with SARS (Tomlinson and Cockram, 2003). Overcrowding in the ward and the poor ventilation systems were suspected to be contributing factors, although no detailed epidemiological studies were cited.

The effectiveness of the air conditioning system in existing hospital SARS wards has been a great concern since the outbreak. In response to this concern, the Hong Kong Institution of Engineers formed an expert group in early May - the SARS-Busters to investigate and develop an air-conditioning system that is suitable for SARS wards. A new SARS ward air conditioning design was completed in late May (SARS Busters, 2003). The new design takes into the major recommendations by the WHO, CDC (US), the Chartered Institution of Building Services Engineers (CIBSE, UK), the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) and local practices for handling of airborne infectious diseases. The new design is well supported by extensive computational fluid dynamics simulations (SARS Busters, 2003). The main idea of the new design is to minimize air mixing and improve virus removal effectiveness in the SARS wards.

The aim of this research is two folds:

1. To construct a new full-scale test room for studying SARS ward air distribution;
2. To test and demonstrate the new air conditioning system for SARS wards.

The full-scale test room was completed in less than 4 weeks time between late May and middle June 2003. The air-conditioning system tests were completed in another four weeks time between middle June and middle July 2003. In this paper, we will first review the ventilation principle for controlling personal exposure of pollutants originated from breathing. Basic principles and considerations of air distribution design in hospital wards are discussed, followed by an introduction of the main features of the full-scale test room. The smoke visualization and aerosol measurement results will then be summarized, followed by a conclusion of the preliminary study and recommendations for further investigations.

2. BASICS OF AIR DISTRIBUTION DESIGN OF HOSPITAL WARDS

Indoor air flows are generally turbulent and it is a complicated process, affected by the details of air distribution design, heat sources, interaction with outdoor environment, movement of occupants etc.

With a view to minimizing cross infection among patients and health care workers inside a hospital that admits suspected and probable SARS cases, the design objectives of the proposed air conditioning system for SARS ward as suggested by SARS Busters are as follows:

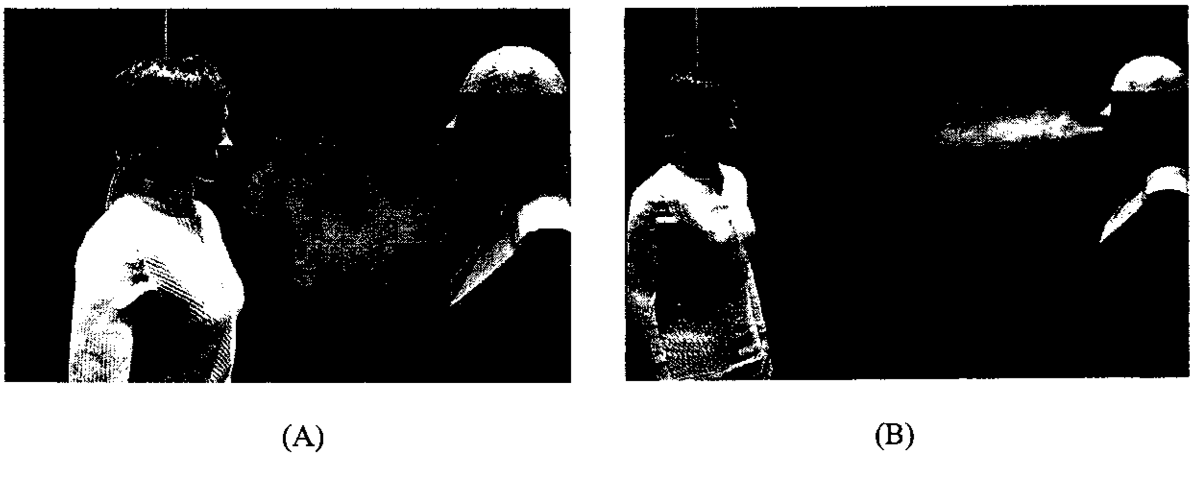
1. to create a negative pressure inside the SARS ward to avoid possible diffusion of contaminated air from getting into the general ventilation of the hospital;
2. to minimize re-circulation and mixing of air inside the SARS ward;
3. to direct airflow from clean zone to breathing zone of health care workers, to patients and then to exhaust;
4. to minimize the expiration of one patient from getting into the breathing zone of the other;

5. to dilute and remove droplet nuclei through controlled purging with outside air;
6. to create a downward airflow pattern from high level to low level to speed up the deposition and removal of droplet nuclei; and
7. to provide task ventilation for individual patients

One difficulty when attempting to design and predict indoor airflow is that there are many factors; which influence or govern the airflow. Quite often some of these factors are difficult to analyse. These factors may be summarised as follows (Li, 1993)

1. The geometry of the room, i.e. a deep or a short room, a narrow or a broad room;
2. The type and location of supply air terminals and the location of extract air terminals;
3. Supply air parameters such as velocity, momentum flux and buoyancy flux;
4. The location, shape and buoyancy flux of heat sources;
5. The location of obstacles and furniture;
6. Radiation and heat loss through the walls;
7. Infiltration and exfiltration through door gaps and other leak areas;
8. Movement of equipment and people;
9. Other factors.

The airflow in the air stream (boundary layer) around the body is generally large, typically about 150 m^3 /hour at head level, while the air speed above an adult's head is typically about 0.2 m/s in a still environment. The inhaled air is generally taken from the boundary layer flow around the body (Etheridge and Sandberg, 1996 and Settles, 2001). However, when someone is lying in his/her bed, the situation can be very different. Studies have also shown that the exhalation flow from both nose and mouth is able to penetrate the breathing zone of another person standing nearby; see Figure 1 (Bjorn and Nielsen, 2002). In thermally-stratified rooms such as those ventilated by displacement, air exhaled through the mouth can even be locked in a thermal stratified layer (Bjorn and Nielsen, 2002).



(A) (B)

Figure 1 – (A) Smoke visualization of exhalation flow from nose of the right manikin penetrating into the breathing zone of the left manikin which are 0.4 m apart and (B) Smoke visualization of exhalation flow from mouth of the right manikin penetrating into the breathing zone of the second manikin of a distance of 1.2 m (Bjorn and Nielsen, 2002).

Considering various possible air flow patterns, one can divide them into four main categories, see Table 1.

Table 1. Ideal and typical airflow patterns in a ventilated room.

Air flow pattern	Air Quality	Air Exchange Efficiency
Unidirectional flow	Supply air conditions	100 %
Displacement ventilation	Supply air conditions in the occupied zone	>50 %
Mixing Ventilation	Extract air conditions	>50 %
Short Circuiting	Worse than extract air conditions in the occupied zone	<50 %

What type of airflow pattern one obtains depends on the relative location of supply and extract terminals, buoyancy sources in the room, momentum of the supply jets and relation between momentum and buoyancy forces. Practically, there are at least three commonly used air distribution systems in non-industrial buildings such as offices, lecture rooms and general hospital wards. These are the momentum-controlled mixing ventilation, buoyancy-controlled mixing ventilation and buoyancy-controlled displacement ventilation systems. In clean rooms and operating theatres, unidirectional flows are generally employed.

Momentum-controlled mixing ventilation - In mixing ventilation, the supply air is used to dilute the contaminant. This is achieved as to supply air with high initial momentum in order to create recirculation of the air. The idea is to create a concentration in the room that is the same as in the extracted air. Generally, the air is supplied along the ceiling or directed upwards along the window wall surface etc. The supply of air is arranged so that the velocities in the jet are reduced to an acceptable level when it arrives in the occupied zone. In practice, the air flow is assumed to be predominantly turbulent, in which case the Reynolds number of the supply air jet is greater than 10^4.

Buoyancy-controlled mixing ventilation - The dilution of the contaminant is also achieved by supplying a high initial momentum. In order to remove excess heat load or cooling load in the room, the supply air temperature is different from the room air temperature. The flow in the buoyant jet is not only turbulent, but larges-scale turbulent eddies also form in the occupied zone due to the interaction of the jet with convective currents produced by the heat sources. Under such conditions, the effect of the Reynolds number of the airflow pattern is small by comparison with the influence of the Archimedes number. That is why we call it the buoyancy-controlled mixing ventilation. In this system, the smallest possible Archimedes number (<0.01) is generally used.

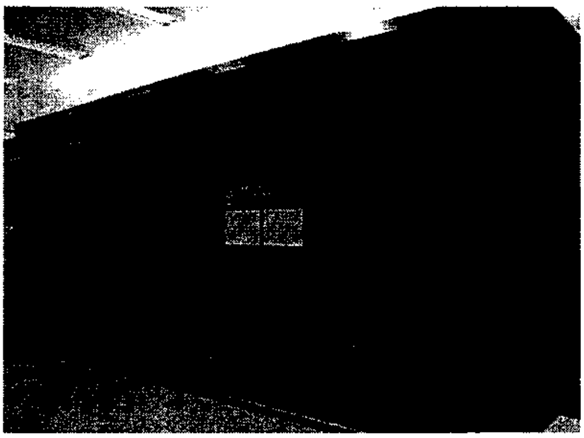
Buoyancy-controlled displacement ventilation - An alternative ventilation method is to introduce "fresh" air in one part of the room and allow it to sweep in one direction across the space, carrying the pollutants with it, and exhaust the polluted air from the opposite side of the room. Piston flow or plug flow often refers to such unidirectional ventilation. The so-called displacement ventilation largely depends on heat sources in the room to provide the upward motion of the air, and uses the supply buoyancy flux to spread the "fresh" air at the floor level. This is why we call it the buoyancy-controlled displacement ventilation. Due to the thermal comfort requirement, the supply air should spread more widely at the floor level with a low air velocity. This requires a large Archimedes number (>0.1), so that a low velocity (<0.3 m/s) terminal with a large opening area is used. The flow from the low velocity supply terminal with cool air (2-4°C below room air) cannot be regarded as a jet, but rather as a gravity current.

It will be seen later that the air conditioning system proposed by SARS Busters can be improved by considering these design principles. If the supply velocity is high as originally designed at 1 m/s, then the supply air stream is a high-momentum jet, which encourages the flow mixing in the room. After various tests, it is found that the supply air velocity can be maintained at less than 0.2 m/s, which will allow a gentle cool air stream falling down to the occupied region as a negative thermal plume. It should be mentioned that this does not mean that there is no flow mixing in the room; however, we believe that the flow mixing is considerably reduced as compared to a room ventilated by a fully mixing system. While the commonly used floor low-velocity supply system is called passive displacement ventilation, the system proposed by SARS Busters is very similar to what is called the active displacement ventilation in Scandinavian countries. However, there is also a difference here – the exhaust is located at both floor and mid height levels, while the commonly used displacement ventilation uses a ceiling return.

3. CONSTRUCTION OF THE FULL-SCALE TEST ROOM

Measurement in a full-scale test room is perhaps the most reliable method of evaluating indoor airflow design. Small-scale test rooms have the difficulty to satisfy the similarity requirements, while the field measurements are influenced by many uncontrolled environmental and physical parameters. The computational fluid dynamics methods always contain errors due to mathematical models, numerical methods as well as users, although very useful as shown in the SARS Busters study (SARS Busters, 2003).

(A) Modular structure

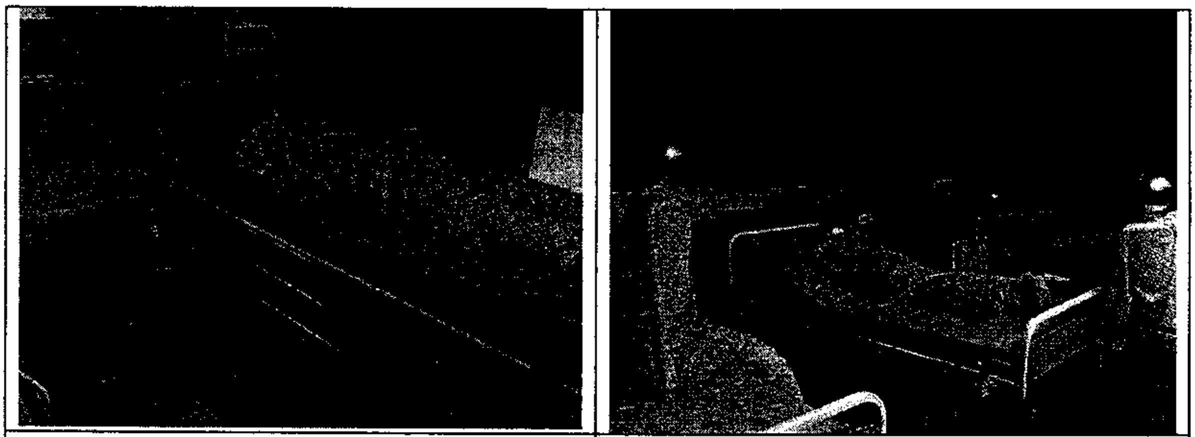


(B) The completed test room

Figure 2. The full-scale test room

The full-scale test room constructed in the Building Services Laboratory at the University of Hong Kong is 6.7 m long, 6.7 m wide and 3 m high, which is a typical ward size in Hong Kong. A 0.3 m suspended ceiling is used to accommodate the supply air ducts as well as lighting. A modular approach is adopted for the test room envelope design; see Figure 2. 1 m by 1 m wall panels and double-glazed windows are used so that the room can be (relatively) easily modified to a different size. Both insulation and double-gazed windows are provided; see Figure 3. The air conditioning system is designed to be as closely as possible to the new design by SARS-Busters, equipped with a 9 ton chiller. Both lighting loads and equipment loads are modeled as closely as possible to the real situations as suggested in the SARS-Busters report.

A rather unique feature of the full-scale test room is the use of seven identical breathing thermal manikins for modeling both patients and HCWs; see Figure 3. These clothed manikins are designed to be much simpler than the thermal manikins commonly found in thermal comfort studies. Made of flexible ventilation ducts and a copper hollow sphere, both head and body temperatures are individually controlled. These simple thermal manikins are made to model the effect of thermal air flows due to the heat generation from the patients. The heat dissipation in both head and body parts are designed to follow average adult figures. Some of the manikins are connected to a simple artificial "lung" that provides exhalation through the mouth. Due to time constraints, these manikins do not have a nose at this point. Thus, we could only model the mouth expiration flows. Existing studies have shown that mouth exhaled flows are more critical than that through a nose (Bjorn and Nielsen, 2002). Most people use nasal breathing when quiet, but use oral breathing while talking and singing.



(A) The manikin with steam supply for modeling exhaled breathing flows.	(B) Part of the test room showing both sleeping (titled beds) and sitting patients.

Figure 3. Simple breathing thermal manikins used in the full-scale test room.

4. TEST RESULTS AND DISCUSSIONS

4.1 Test conditions

In order to test the performance of the proposed new air conditioning systems, we have considered the following eight test cases. The various test conditions are summarized in Table 1. During the tests, there were some variations in both the supply and exhaust air flows.

4.2 Smoke visualization

During the smoke visualization tests, smokes are generated by a smoke generator and released into either the supply duct or through the source patient's mouth. Air temperatures are monitored by thermal-couples; and air speeds at both the supply and exhaust are monitored by hot wires.

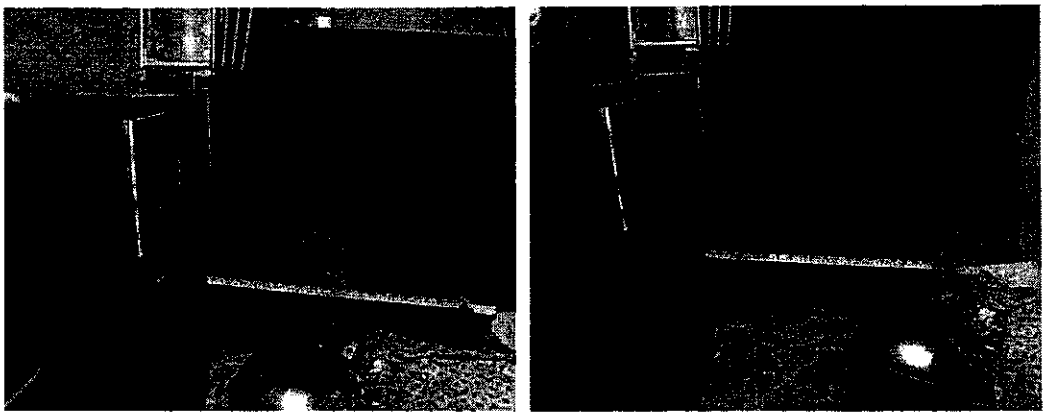
For each case defined in Table 1, we first switch on the supply and exhaust fans, lights, and the thermal manikins' power, followed by adjusting both supply and exhaust air flow rates to as closely as possible to the specified values. Smoke visualization is done after at least one hour so that a steady state may have achieved. There is unfortunately some periodic variation in the supply air temperatures due to the use of a very large chiller, which has made it difficult to control the supply air temperature as the test room has a very low cooling load. Due to the unsteady supply air temperatures, smoke is released only when the supply air temperature is less than 17°C for the tests carried out in this study.

Table 1. A list of test conditions.

No.	Purpose	Description of Conditions
1	**Standard case**	Supply flow rate is 362 l/s & exhaust flow rate 456 l/s. Bed-head and below-bed exhaust ratio is 10:90. The door is closed and no local hood is used.
2	Effect of retractable local hood	Same as Case 1; except a local retractable hood is used for the source patient.
3	Effect of door opening	Same as Case 1; except the door is open.
4	Effect of bed-head and below-bed exhaust ratio	Same as Case 1; except the bed-head and below-bed exhaust ratio = 30:70.
5	Effect of bed-head and below bed exhaust ratio	Same as Case 1; except the bed-head and below bed exhaust ratio = 50:50.
6	Effect of middle duct supply air flow rate	Same as Case 1; except that the middle air ducts grilles supply 50% more than other grilles
7	Effect of people movement	Same as Case 1; except that one person walks in the room
8	Effect of no head-level exhaust	Same as Case 1; except the bed-head and below bed exhaust ratio = 0:100.

For the exhaust air flow pattern, there are two important parameters, both related to the distance between the nose and exhaust. We located the manikin so that the manikin was just 100 mm below the exhaust grille. We then gradually moved the manikin away from the exhaust grille to observe the changing capture effectiveness. The horizontal distance between the manikin and the exhaust is measured by the distance between the manikin head and the grille.

Figure 4 shows some typical exhaust flow patterns. If the patient's head is more than 100 mm away from the exhaust, the capture efficiency is reduced to zero for Case 1. Using a higher extraction ratio at bed-head level exhaust or using the retractable hood can improve this constraint in the effective capturing distance. At an extraction ratio of 30:70, the critical capturing distance increases to 200 mm. We suggest that a 30:70 exhaust ratio is a suitable option for this test room. It should be noted that this optimum extraction ratio should not be used universally in all situations as the airflows are affected by many other parameters. Either computational fluid dynamics simulations or full-scale tests will be necessary to verify the optimum design parameters for a new design.



Horizontal distance between the grille and the head top is 100 mm

Horizontal distance between the grille and the head top is 300 mm

Figure 4. Smoke visualization of the exhaust air streams for two different distance between the patient and the exhaust grille. Extraction ratio is 10:90.

The supply air streams are clearly shown in Figure 5. Due to the relatively low velocity that is used for supply (less than 0.2 m/s), the supply "jets" may be best described as "negative thermal plumes", which means that the primary supply air flow is dominated by the negative buoyancy force as the supply air is relatively heavier than the surrounding. Thus, it is expected that the airflow pattern will be mostly affected by the cooling load in the room. If the cooling load is low, then the supply air temperature is high, and there may not be sufficient negative buoyancy force to drive the air flow downwards. The use of low velocity supply also enables us to use 9 large supply grilles to provide task ventilation to both HCWs and patients.

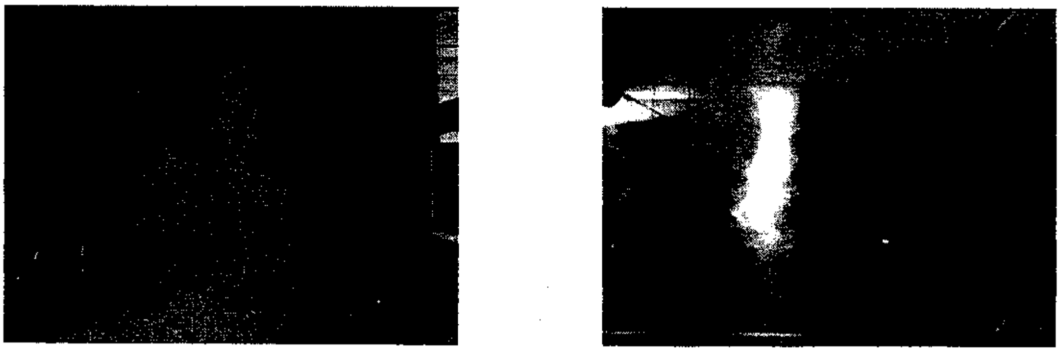
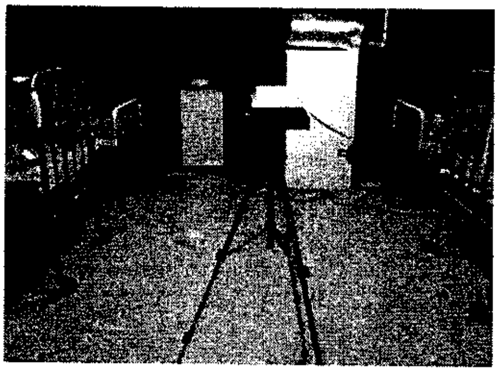


Figure 5. Smoke visualization of the supply air streams in the test room for the standard conditions, Case 1. (A) Supply air stream from one supply grille. (B) Supply air streams from several supply grilles.

4.3 Aerosol concentration measurement

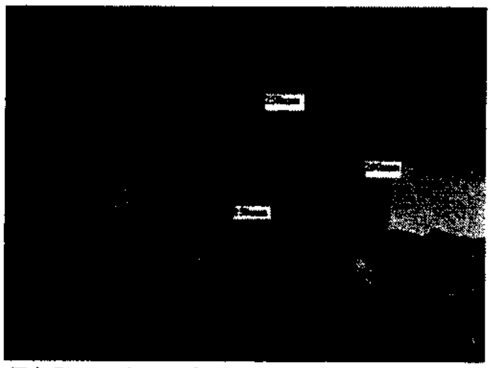
Smoke visualization are qualitative. Quantitative measurements would assist our evaluation of the air conditioning systems to identify the optimum design parameters. This was done by placing an aerosol generator in one bed and aerosol concentration measurement is carried out for three locations – the source patient bed, the middle corridor (HCWs) and the neighboring bed. For the source patient, the aerosol generator is released through a flexible plastic tube connecting to the patient's mouth. The positioning arrangement is shown in Figure 6. As there is only one dust meter, we have carried out the measurement one after another and each measurement takes about 2-3 minutes for sampling. Each set of measurement takes about 10 minutes. Due to the presence of the people during the measurement, some mixing may be introduced due to body air flows of the person and his movement.



(A) Dust meter location in the corridor

(B) Dust meter location in patient's bed

(C) Simulation of a sitting patient



(D) Location of source patient's mouth for aerosol measurement

Figure 6. Photos for some experimental arrangements.

Table 2. Summary of measured aerosol concentrations excluding the background dust level.

Case No.	Source Patient (μg/m³)			HCW (μg/m³)			Neighbor bed (μg/m³)		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1	**42**	22	75	**9**	0	18	**14**	4	25
2	**86**	30	177	**-3**	-9	7	**5**	-1	17
3	**62**	40	86	**-2**	-8	3	**18**	0	111
4	**21**	4	42	**5**	1	16	**23**	2	46
5	**-3**	-8	2	**-2**	-5	11	**1**	-7	19

6	**64**	18	211	**19**	10	30	**42**	25	78
7	**48**	24	168	**3**	2	5	**33**	24	54
8	**249**	214	276	**200**	165	232	**207**	172	228

Table 2 summarizes the measured concentrations after adjustment by the ambient background dust levels. Case 1 is the standard case with a bed-head and below bed exhaust ratio of 10:90. A reasonably high level of aerosol levels is recorded at both the HCW location and the neighboring bed (Bed 5 in Figure 7). Due to the unsteadiness, some negative adjusted concentrations were also obtained.

The 50:50 exhaust ratio gives the best results of all three ratios tested. However, due to the relatively high extraction velocity, the 50:50 extraction ratio is not recommended for use. The use of the retractable hood also provides a good protection for both HCWs and other patients. It should be noted that the existing retractable hood design could be improved by locating the exhaust outlet at the top of the hood to reduce the aerosol concentration for the source patient (Case 2). Both motorized operation and disposable design are possible.

When opening the door of the test room, there is a strong airflow into the test room through the entrance, which causes the concentration for HCWs to be reduced. The mixing induced by the door airflows also caused severe "cross-infection" between beds. Higher middle duct supply was originally intended for providing higher air velocity and lower air temperature for doctors and nurses who are likely to have high clo and met values. The present results show that if the middle air supply is not properly controlled, the high air supply momentum may be responsible for more air mixing as shown for Case 6. Possible solutions may include the use of larger supply grille areas to reduce the supply air velocity. The people movement in the room can also affect the airflow pattern adversely. Mixing is introduced when people move in the room. The degree of mixing depends on the speed and direction of movement.

4.4 The retractable local exhaust hood

The local hood is found to be very effective in removing the virus-laden aerosols. With the hood, the virus-laden aerosols originated from the patient's mouth can be captured fully even when the patient is more than 300 mm away from the exhaust. Obviously, the patient's head should be covered under the hood to obtain the 100% capture efficiency. It is found that the exhaled airflow direction is also an important parameter. If the patient faces outside and the exhaled airflow is directed to the surrounding, the virus-laden aerosols can escape into the test room.

A number of critical comments have also been received from the visiting medical professionals on other aspects related to infection control. For example, the plastic materials used for the prototype hood may not be adequate due to the possible difficulties in surface cleaning. It is recommended that the retractable hood may be built to be light structure, disposable or washable, and can be easily hooked on or off to the wall. The local hood design still needs to be improved with inputs from the medical professions.

4.5 Opening the entrance door

There is a negative pressure when the door is closed. When the door is open, the negative pressure drives the airflows from outside to the test room. The airflow can be very strong depends on the magnitude of the negative pressure. This incoming airflow from the door can destroy the negative supply plume from the supply grille near the door, and cause significant mixing in the test room.

It should be mentioned that door opening may not always cause incoming air flows. The airflow through a doorway also depends on the temperature difference between the ward and the outside. If there is a significant temperature difference, the stack force can also introduce significant airflows.

4.6 Bed-head and below bed exhaust ratio

One innovative feature in the SARS-Busters' design is the use of bed-head level exhaust to provide some local-capturing effect. Questions have been asked what extract ratio is the most effective one. To answer this question is not easy and the CFD results have shown that the 10% exhaust at the bed-head level was the most efficient (SARS Busters, 2003). However, our full-scale tests have revealed that a high extract ratio at the bed-head level is more effective in terms of removing the exhaled air from the patient if the patient is not too far away from the exhaust.

This is obvious as the flow into an exhaust grill is a potential flow. The air velocity decays quickly as it moves away from the grille ($V_r = \frac{V_0}{r^2}$, where V_r is the velocity at a distance r from the grille and the V_0 is the air velocity at the grille when $r = 0$). A high exhaust flow rate would result in a high exhaust velocity through the grille when the exhaust area is kept the same and thus also result in a high capture-efficiency. The effectiveness of local exhaust is also demonstrated in the aerosol concentration measurement.

A 50% exhaust at the bed-head level will improve the capture efficiency. Even the patient is 300 m away from the exhaust; the removal is still visible in smoke visualization. The effect of exhaust ratio on the overall flow pattern, in particular on the supply air streams is negligible. This may be due to the nature of flow, driven by the negative buoyant plumes of the supply grilles. However, when the bed-head level exhaust is closed (extraction ratio 0:100), then a significant increase of aerosol concentration in all locations in the room is detected (Table 2, Case 8). This is simply due to the fact that the source is spread into the rest of room.

4.7 Middle grilles supply 50% more than the patient head supply grilles

A higher-middle air duct supply is considered due to the need to satisfy the different requirement in thermal comfort for the patients and the health care workers. Health care workers seem to have a higher clo value, while the patient can wear much less. Health care workers also move around in the room and work, which may indicate that health care workers may also have a high met value. This means that health care workers may prefer a different room environment, although no systematic studies have been carried out.

A higher middle air duct supply would provide a higher air speed in the corridor area and may provide a cooler environment for the health care workers. Site measurements are needed to examine the nature of the thermal comfort requirements of health care workers and the patients. Some medical visitors to the mock-up ward have suggested that health care workers actually prefer "draught" during the SARS outbreak, while other medical professions denied such a phenomena. These confusing observations suggest the need of carrying out detailed investigation in the hospital environment. If no knowledge is available about the thermal comfort requirement of patients and health care workers, it is very difficult to design an effective air conditioning system for hospital wards. Future tests would include the use of more one additional supply grilles so that the supply air velocity is not increased, which would help to minimize the flow mixing, but creates a cooler environment for the walking HCWs in the corridor.

4.8 Dispersion from the source patient to other beds

We also measure the aerosol concentrations in all beds to access the possibility of cross-infection in the test room. This is done by placing the aerosol generator in one patient's bed, Bed 6 in Figure 23. Measurement of aerosol concentrations is carried out for all other beds and the middle corridor.

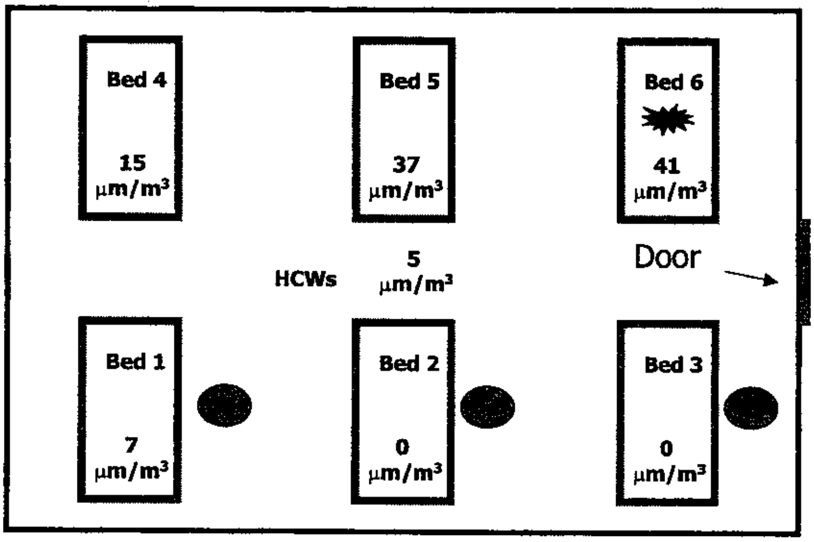


Figure 7. Illustration of the location of source patient, other patients and health care workers (HCWs). Measured mean values of aerosols orginated from the source patient are also shown. Negative adjusted concentrations in Table 3 are indicated by a aero value.

Table 3. A summary of the measured aerosol concentrations for all beds in the test room excluding the background aerosol levels.

Locations	**Aerosol concentration (µg/m³)**		
	Mean	**Min**	**Max**
Bed 1	7	3	24
Bed 2	**0**	-8	26
Bed 3	**0**	-4	3
Bed 4	**15**	10	26
Bed 5	**37**	18	65
Bed 6(source patient)	**41**	26	71
HCW	**5**	0	17

Table 3 summarizes the measured concentrations at various locations in the room when the aerosols are generated near the source patient's mouth in Bed 6. There is a mixing in the source patient side of the test room. All beds in this half of the room have recorded relatively high virus-laden aerosol concentrations. It indicated the difficulty in controlling the unidirectional flows in the test room. The body buoyancy flows may be responsible for the between-bed mixing. A variation of the system would to place the supply grilles between beds, rather above a bed. On the other hand, the concentrations in the other half of the room are relatively very low, suggesting that the middle ducts play an important role in "separating" the airflow between the two sides of the room as an "air curtain". It should be noted that Bed 1 recorded a relatively higher dust concentration than Beds 2 and 3. This may be due to the use of a cooling fan for the thermal manikin controller, which is located between Bed 1 and Bed 2. The fan is sufficiently strong to cause some local mixing in the region, which might have caused some particles on the beds or the floor to be re-suspended.

5. CONCLUSIONS

The new air conditioning system designed by SARS-Busters air distribution is shown to perform well for a nearly realistic full-scale SARS ward. The new bed-head exhaust design allows some degree of local capture of the virus-laden aerosols, originated from patient's mouth. A 30 to 70 ratio between the bed-head level and below-bed extraction is found to be a suitable exhaust ratio. If the simple and innovative retractable hood is used, the cross-infection between the patients is totally eliminated for the test conditions considered. People movement and door opening are shown to introduce significant mixing in the test room. Air distribution in SARS wards is shown to be a complicated process and proper design is necessary for minimizing cross-infection between patients and between patients and HCWs and efficient and effective dilution and removal of virus-lade aerosols. Airflow patterns are also found to be very sensitive to minor changes in the supply grille and supply air parameters.

Based on the preliminary results obtained from this mock-up study, design guidelines from CDC, WHO and ASHRAE and local practices, the following design principles are recommended for the SARS Ward:

- If possible, single occupancy ward design with a separate air conditioning system is always preferred.
- Negative pressure in the patient room needs to be maintained.
- A minimum of 12 air changes per hour outdoor air supply is recommended.
- Low-level exhaust is preferred together with a ceiling downward supply. For ceiling level supply, the supply air velocity should be maintained between 0.1- 0.3 m/s.
- Task ventilation is recommended with each supply grille and exhaust grille for each bed as well as dedicated supply grilles for health care workers in the middle corridor region.
- The bed-head exhaust is very effective for sleeping patients. This should be promoted if space allows and if hospital infection control has no objection to its position. Other designs such as retractable hoods may also be considered.
- If a bed-head level exhaust is used, a 30 to 70 ratio between the bed-head level and below-bed extraction is found to be suitable. Noise could be a problem if exhaust grille air velocity is too high.
- The ventilation system designed by SARS Busters appears to provide good contamination control for HCWs and the opposite patient beds. Adjacent patient bed is not as well protected. It is recommended to always put patients in opposite beds first.

- Air distribution in SARS wards is shown to be a complicated turbulent process and proper design using computational fluid dynamics simulations, laboratory testing or even field mock-up is considered to be very important.
- Testing and commissioning is critical. Apart from the conventional items such as flow balancing etc, testing and balancing should include a check of supply air streams, which can be easily done by using smoke visualization.

In summary, the basic design principles in the SARS-Busters design are shown to be useful by the preliminary full-scale mock-up study at HKU, and they should be followed if possible.

ACKNOWLEDGEMENT

The Faculty of Engineering of the University of Hong Kong and the Hong Kong Institution of Engineers SARS Fund financially supported this project. Installation, testing and commissioning of the air conditioning system for the mock-up room are coordinated and carried out by Ir Victor Law of Atal Engineering. More than 200 medical professionals, hospital engineers and officials from Hospital Authority, EMSD, Department of Health, Policy Bureau, various hospitals etc have offered various valuable suggestions and comments for improving the system design and testing procedures during their visits to the test room.

HKU team also like to thank Ir Victor Cheung, Convener of the SARS-Busters' mock-up study, Ir Frank Fan Chan, Convener of the SARS-Busters' concept development, and all SARS-Busters. Through emails, meetings and visits to the mock-up room, all SARS Busters have offered valuable comments, suggestions and supports. Without the dedicated contribution of all SARS Busters, the ward construction would not have been possibly completed within a very tight schedule. The HKU team also wishes to thank all donors and supporters during all phases of the project.

YL would also like to thank Dr Xiaoling Wang of Ericsson, Sweden and to Dr Eric Bjorn, Aalborg University, Denmark for providing details on breathing thermal manikins. Dr Eric Bjorn provided the original files of Figure 1. Colleagues in the building services laboratory, Ir H N Lam, Dr Sam Hui and Dr Michael Leung have actively participated in the initial design process of the test room and offered their support during testing and demonstrations. Mr Leung Wing Kam acted as the lab coordinator for this project. He also designed and constructed seven breathing thermal manikins. Mr Qian Hua conducted all the measurements. Leung Mr Kwan Siu Wah, Ms Shuangping Duan, Mr Jerry Chan and Mr Albert Lee from HKU also contributed the project in one way or another.

List of donors and supporters

HKIE SARS Fund (financial support); Faculty of Engineering, HKU (financial support); Atal Engineering Ltd (AC installation, testing and commissioning); Efatar (chiller and primary air unit); Johnson Control (perforated diffusers); Air Trade Centre (pre-fabricated PU ducts); Meco Engineering (Lighting panel); Leo Engineering (construction of the room envelope); QMH (hospital beds and lockers); AET Flexible space (laboratory equipment); City University (laboratory equipment); HKUST (laboratory equipment support); PolyU, (laboratory equipment support) and City Hall (stage lighting system)

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