Development of an extraction equipment for preventing the transmission of contaminant exhaled air

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Abstract

In 2003, the World Health Organization received reports of 'Severe Acute Respiratory Syndrome (SARS)' in various parts of the World. Until 13 June 2003, there were 1755 people affected by atypical pneumonia in Hong Kong. While the mechanisms of the SARS are till under investigation, much information was released that enabled engineers to develop a system to reduce the risk of spreading of SARS in hospitals. The outbreak of SARS also prompted building services engineers to review the current air circulation patterns around patients who are indoors with the objective to develop a new type of system to reduce the risk of microbial disease.

This study developed personal respiratory protective equipment with the capability of reducing the risk of nosocomial transmission of SARS. While the prototype was being established, airflow, velocity profile measurements and smoke tests were performed. It was found that the performance of the extractor correlated well with the design specification.

INDEX TERMS

Hospital; Contaminant distribution; Instrumentation, Indoor air quality

INTRODUCTION

On 21 February 2003, a professor in Zhong Shan University brought an unknown virus into Hong Kong, which is now identified as a type of Corona Virus. It triggered an outbreak of what World Health Organization (WHO) named as Severe Acute Respiratory Syndrome (SARS). It is highly contagious. Nosocomial transmission of SARS has been associated with close contact of persons who suffered from SARS and with the performing of certain high risk procedures (e.g. bronchoscopy, endotracheal intubation and suctioning, open abscess irrigation and autopsy). However, there have not been any detailed investigation of the administrative measures and development of new building services systems to reduce the recognized risk to the healthcare workers.

There is a need to study the interaction of these droplets with the ventilation patterns induced by the airside system. The result is obviously very important in understanding the spread of the droplets in air and its pattern of deposition on surfaces. It helps to realize how these droplets are received on an intercepting body, and for cleaning and sterilizing procedures. The conventional design of the air-conditioning system is for human comfort in terms of thermal comfort and indoor air quality comfort, and works on a 'perfect mixing' pattern. This outbreak of SARS, though painful, triggers an alarm to the building services industry. The research team in the past few years has been concentrating on the research of improving and enhancing the Indoor Air Quality (IAQ) from the health aspect. The BSE Department, in particular, has produced an economical and effective sampling protocol and a ventilation system performance monitoring protocol. In this urgent situation, the research team therefore heads towards the development of engineering systems to prevent the spread and reduce the concentration of infectious droplets and personal respiratory protective equipment in areas where there is still a risk for exposure to SARS.

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DESIGN RATIONALE AND METHODOLOGY

Direct source control and general ventilation are two methods to prevent the spread and reduce the concentration of infectious droplets. The contemporary prevalent general airside systems in buildings are Variable Air Volume (VAV), Constant Air Volume (CAV) and Fan Coil Units (FCU). The conventional VAV, CAV and FCU systems all employ the 'perfect mixing' principle. This will unavoidably mix all the pollutants in indoor space before they are recirculated for exhaustion or re-conditioning. The displacement system (DS) has the advantage of limiting the diffusion of the pollutants, but extensive integration into the building and indoor decoration by the DS limits its use in the high rise offices in Hong Kong. One vital problem of the conventional design, with respect to virus spread, is the lack of a method to control the path of the contaminant air. For general ventilation, it consists of dilution and removal of contaminants; airflow patterns within rooms; airflow direction in facilities and negative pressure in rooms. With urgent need for manpower and resources in health care facilities at present, it is very difficult to modify the existing ventilation system at this critical period. Therefore, direct source control with air cleansing is the only method to capture the contaminants at or near the source and remove the contaminant without exposing persons in the area to infections agents (ACGIH, 1992).

If the air is discharged into the room, a filter should be incorporated at the discharge duct of the extractor. The exhaust fan should be located on the discharge side of the filter to ensure that the air pressure in the filter housing and booth is negative with respect to the adjacent areas. Uncontaminated air from the room will flow into the booth through all openings, thus preventing the infectious droplet in the booth from escaping into the room. Most commercially available booths, tents and hoods are fitted with filters (Brian, 1994). They should also be designed to ensure adequate air mixing in all areas of the hospital rooms in which they are used, and they should not interfere with the current ventilation system. In addition, a pre-filter can be installed to increase the life time for the filter.

In order to reduce the risk for transmission of SARS, photoactive titanium dioxide filtration units are employed for disinfecting air. Ultraviolet Germicidal Irradiation (UVGI) units were installed in ducts to irradiate air passing through the ducts. An UVGI unit installed in ducts should not be substituted for filters in ducts that recirculate air back into the same room.

According to the Bernoulli equation, the velocity of a fluid is as follows [it is assumed that ambient pressure is the standard 101 kPa, the duct pressure is no more than 5 kPa different from the ambient pressure, the dust loading is low (0.2–2 g/m^3) and moisture is not a consideration, for a standard air density of 1.2 kg/m^3]:

$$V = 1.29\sqrt{VP_{\mathrm{d}}} \qquad (1)$$

$$Q = V \times A \qquad (2)$$

where VP is the velocity pressure of the duct (Pa), V the velocity (m/s) and A the area (m^2).

The hood is the most important part of the system to catch the contaminants into the system. The selection of the hood shape and location depends on the source of contamination. The hood entry is calculated from the hood entry loss factor and the air velocity (Henry, 1977). The hood static pressure is the acceleration loss plus the hoods entry loss:

$$SP_{\mathrm{h}} = \text{Acceleration+Hood Entry Loss}$$

$$SP_{\mathrm{h}} = 1 \times \text{duct velocity pressure} + F_{\mathrm{h}} \times \text{duct velocity pressure} \qquad (3)$$

$$SP_{\mathrm{h}} = (1 + F_{\mathrm{h}}) \times VP_{\mathrm{d}} \qquad (4)$$

where SP_h is the hood static pressure (Pa), F_h the hood entry loss factor (dimensionless) and VP_d the duct velocity pressure (Pa).

After performing a design calculation, the types of losses and the magnitude obtained are listed in Table 1.

Table 1 Calculation of the pressure loss in the personal respiratory protective equipment

Type of loss	Magnitude—Pa (inch of water)	Remarks
Acceleration loss	100 (0.4)	
Hood entry loss	25 (0.1)	45° taper
Duct friction loss	50 (0.2)	ϕ200 mm flexible duct
Turbulence loss	150 (0.6)	1 no. of elbow; @ 0.1 inch of water; 1 no. of entry; @ 0.1 inch of water; 2 nos of enlargements or contractions; @ 0.2 inch of water
TiO_2 filter and pre-filter (optional)	25 (0.1)	
Total	350 (1.4)	

In general terms, a normal person moves approximately 500 ml of air in and out of the lungs with each breath and takes 15 breaths each minute at rest. The minimum minute ventilation rate of the equipment is therefore 500 ml × 15 breath/minute = 7500 ml of air per minute (0.13 l/s). When a 400 × 400 mm exhaust hood is selected to cover the face of the patient and a face velocity of 1 m/s is maintained to extract the droplet from patient, a volume of 160 l/s needs to be removed and a convenient way of meeting this requirement is by connecting the flexible tube (200 mm diameter) to the personal respiratory protective equipment (Figure 1). In order to confirm the performance of the exhaust hood, the capture velocity should be identified to overcome the opposing air currents and to capture the contaminant air by causing it to flow into the hood. For the condition of dispersion of contaminant, it is assumed that there is an active generation into the zone of rapid air motion (1–2.5 m/s). The choice of values depends on several factors (Table 2) (ACGIH, 1992). In addition, with the flexibility for modulating the fan speed, a frequency inverter is proposed in the personal respiratory protective equipment.

Table 2 Factors for selecting the values of capture velocity

Lower end of range	Upper end of range
Room air currents minimal or favourable to capture	Distributing room air currents
Contaminants of low toxicity or of nuisance value	Contaminants of high toxicity
Intermittent, low production	High production, heavy use
Large hood—large air mass in motion	Small hood—local control only

A photoactive titanium dioxide filter should be installed to prevent leakage between filter segments and between the filter bed and its frame. A regularly scheduled maintenance programme is required to monitor the filter for possible leakage and for filter loading. A quantitative leakage test should be performed at the initial installation and every time the filter is changed or moved (ASHRAE, 1992). Installation of the filter should allow for maintenance that will not contaminate the delivery system or the area served. The scheduled maintenance programme should include procedures for installation, removal and disposal of filter elements. Filter maintenance should be performed only by adequately trained personnel.

In addition, filter housing and ducts leading to the housing should be labelled clearly with the words 'Contaminated Air' (or a similar warning). Any service personnel dealing with the filtration systems should wear a face mask at all times when they are on duty. Filters dismantled for cleaning or replacement purposes should be put in plastics bags and be handled with care to avoid re-entrainment of trapped particulates.

Figure 1 Personal respiratory protective equipment.

Research has demonstrated that UV unit is effective in killing or inactivating tubercle bacilli under experimental conditions (Riley *et al*., 1957, 1962; Riley, 1988; Riley and Nardell, 1989; Stead, 1989) and in reducing transmission of other infections in hospitals (McLean, 1961). UV Germicidal Irradiation lamps are placed inside ducts that remove air from rooms to disinfect the air before it is recirculated. When UV duct systems are properly designed, installed and maintained, high levels of UV radiation may be produced in the duct work. The only potential for human exposure to this radiation occurs during maintenance operations.

In 1972, the National Institute for Occupational Safety and Health (NIOSH) published a recommended exposure limit (REL) for occupational exposure to UV radiation (NIOSH, 1972). The REL is intended to protect workers from the acute effects of UV exposure (e.g. erythema). However, photosensitive persons and those exposed concomitantly to photoactive chemicals may not be protected by the recommended standard.

The NIOSH REL for UV radiation is wavelength dependent because different wavelengths of UV radiation have different adverse effects on the skin and eyes (NIOSH, 1972). Relative spectral effectiveness (S sub l) is used to compare various UV sources with a source producing UV radiation at 270 nm, the wavelength of maximum ocular sensitivity. To protect people who are exposed to germicidal UV radiation for 8 h per workday, the measured irradiance (E) should be less than or equal to 0.2 uW/cm^2. This is calculated by obtaining Effective irradiance (E_{eff}) (0.1 YuW/cm^2) (Table 3) and then dividing this value by S sub l (0.5).

Table 3 Maximum permissible exposure times for selected values of effective irradiance (NIOSH, 1972)

Permissible exposure time per day	8 h	4 h	2 h	1 h	30 min	15 min	10 min	5 min	1 min	30 s
Effective irradiance (E_{eff}) (uW/cm^2)	0.1	0.2	0.4	0.8	1.7	3.3	5.0	10.0	50.0	100.0

This design is expected to have a capability of reducing risk of the nosocomial transmission of SARS under emergency situation. The effectiveness of such a design will be confirmed by the tests in the environmental chamber and Computer Fluid Dynamic (CFD) simulations.

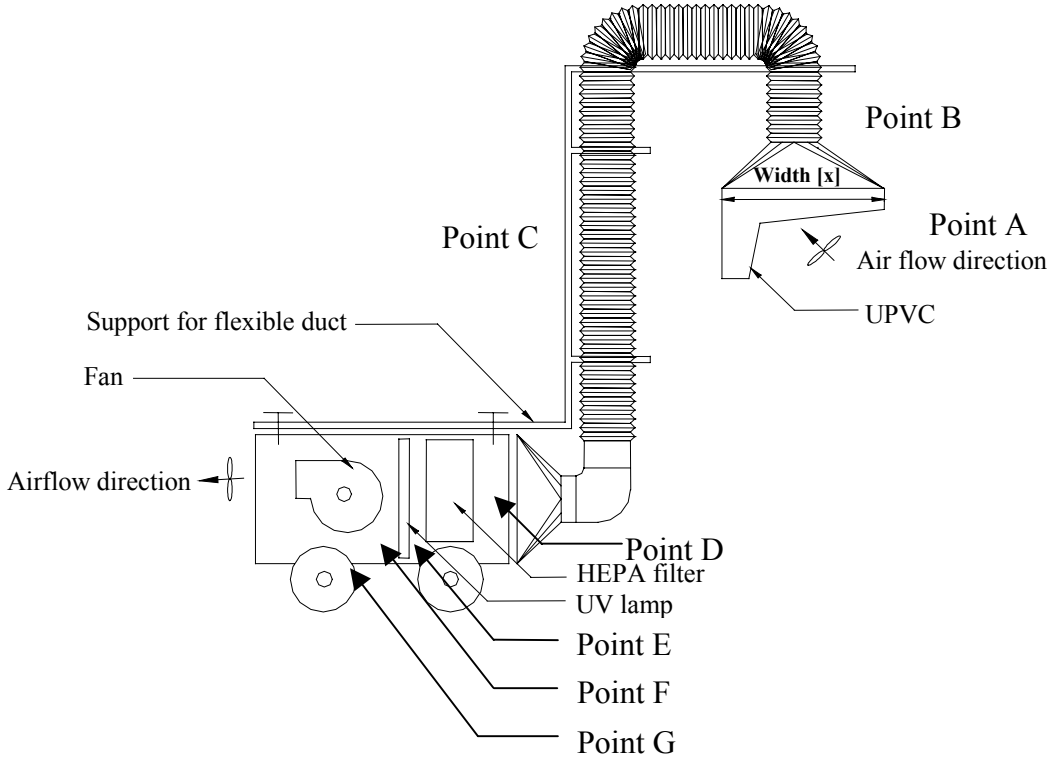
VALIDATION OF THE EXTRACTOR

For the new design, measurements were taken to verify the performance of the extractor: (i) exhaustion rate; (ii) air distribution pattern and (iii) contaminant control. In testing and commissioning, airflow, velocity profile measurements and smoke tests.

Airflow and Velocity Measurements

Air measurements included velocity and static pressure measurements in the system, static pressure measurements at each opening, static and total pressure measurements at both fan discharge and suction. The detailed locations and the results for measurement are listed in Tables 4 and 5. Pitot tubes, pressure gauge and air velocity meter were selected to perform the tests. For the static pressure, velocity and total pressure profile through the extractor is plotted in Figure 2, the velocity contour for the exhaust hood is demonstrated in Figure 3. From the measurement, it was found that a capture velocity of 1.58 m/s is sufficient to capture the droplets produced by the patient.

Table 4 Locations of measurement for the ICU extractor



Point	Measurement	Location of measurement	Measurement use
A	Hood static pressure	Distance from hood—1 to 3 pipe diameters	Estimate airflow Check point for hood and system performance
B	Velocity and static pressure	Branch and main—about 7.5 diameters straight run downstream from nearest air disturbance (e.g. entry)	Transport velocity Exhaust volume: $Q = VA$ Static pressure (SP) as system check point
C	Centreline velocity pressure (*VP*)	Centreline velocity reading only	
D, E, F & G	Static, velocity and total pressures	As shown in above figure	Fan static and total pressure *SP* as system check point

In addition to the above, face velocity (hood face) and capture velocity (point of contaminant dispersion) measurements were performed to define hood performance. Observation of airflows surrounding exhaust openings visually augmented by use of smoke generators.

Table 5 Measurement record form for extractor

Hood and transport velocity

Point	*VP* in Pa	*SP* in Pa	*TP* in Pa	Meter per second (m/s)
A	0.02	–0.94	–0.92	1.58
B	7.06	–30.41	–23.35	5.76
C	20.88	–35.03	–14.15	4.89
D	41.81	–47.26	–5.45	1.63
E	52.33	–55.84	–3.51	0.57
F	53.72	–58.35	–4.63	1.28
G	6.54	–2. 68	3.86	1.78

Pitot transverse (30 Hz)

Point	Velocity
1	4.28
2	4.62
3	4.92
4	5.15
5	5.2
6	5.15
Average velocity. (m/s)	4.89
Litre per second (l/s)	153

Capture velocity: 1.58 m/s.

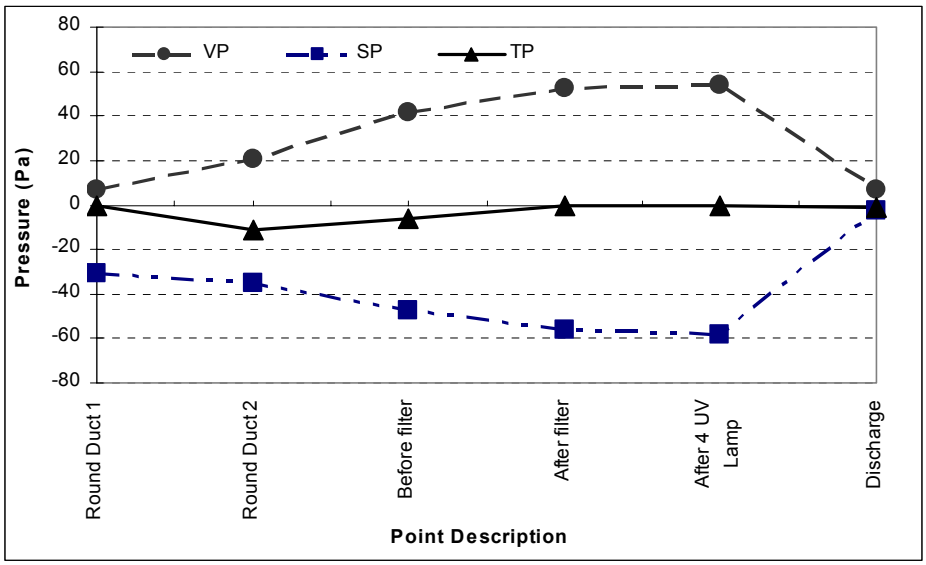


Figure 2 Static, velocity and total profile in extractor.

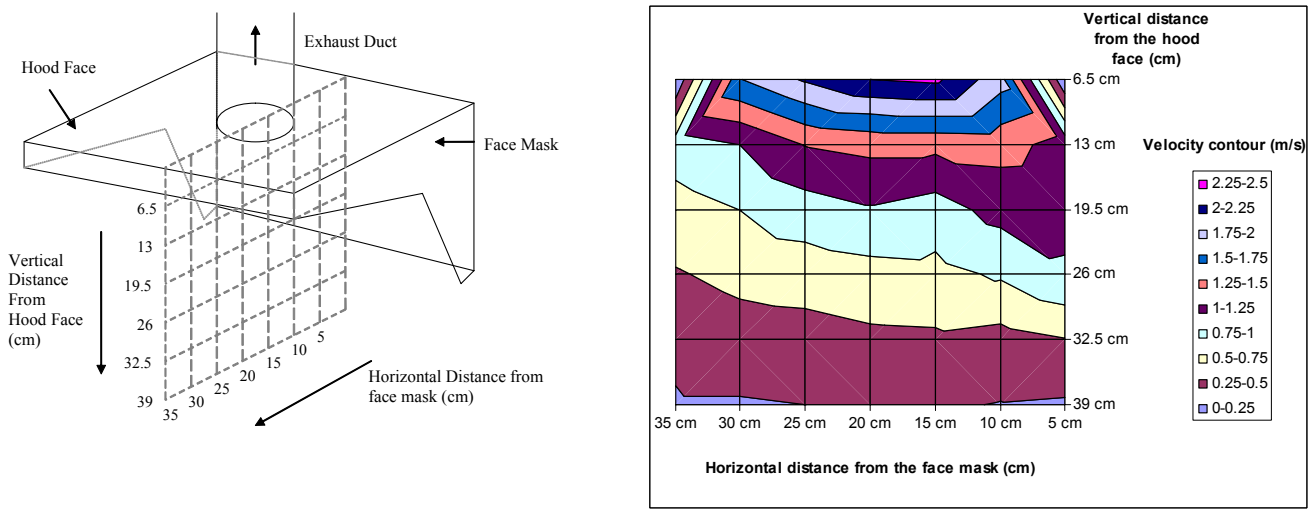


Figure 3 Velocity profile for the extraction hood.

Smoke Test for Visual Inspection

The outcomes were used to valid the performance of the extractor. The propagation of the droplets enabled to visualize the performance of the extraction air path which deposited on surfaces of the hood (Figure 4).

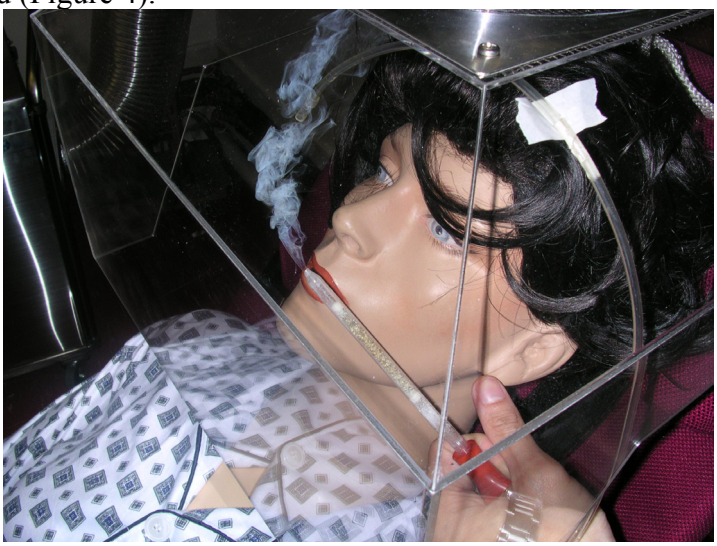


Figure 4 Smoke profile for the extraction hood.

CONCLUSION

The outbreak of SARS has initiated the building services engineers to review the current air conditioning system design. Due to an urgent need, the department of Building Services Engineering developed a personal respiratory protective equipment to reduce the risk of the nosocomial transmission of SARS. One prototype was established and it was found that the airflow, air velocity and flow pattern of the extractor has good correlation with the design specification. For the airflow and velocity profile measurements, the extraction airflow rate and the capture velocity were found to be 1.58 m/s and 153 l/s (the design extraction rate was 160 l/s), respectively.

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