

Local Exhaust Ventilation for Infection Control in Hospitals

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Health care workers (HCWs) treating infectious patients, such as Severe Acute Respiratory Syndrome (SARS) patients, are at high risk of nosocomial infection. The concern is particularly serious during the bioaerosol-induced procedures, in which droplets and bioaerosols emitted by an infectious patient may enter the respiratory system of the HCW in close contact with the patient. These medical procedures include endotracheal intubation, bronchoscopy, ambu bagging, among others. Infection control professionals have identified local exhaust ventilation (LEV) as a promising solution to remove the contagious pollutants for protection against nosocomial transmission of diseases. In this study, computation fluid dynamics (CFD) models were developed to simulate the transport of droplets and bioaerosols for design optimisation of a LEV system, taking into account the important particle deposition and turbulence effects. A LEV prototype was built and tested. The details of the computational analysis and empirical results are presented in this paper.

Keywords: Droplets, Bioaerosols, Local Exhaust Ventilation, Computational Fluid, Dynamics (CFD)

Nomenclature

D	outer diameter of LEV hood (mm)
d_p	particle diameter (μm)
H	maximum distance from the hood face to a given velocity contour in the axial direction (mm)
U	air speed inside the LEV extraction arm (m/s)
V_p	velocity of particle emitted from source (m/s)
W	width of velocity contour (mm)
x	distance between the center of hood face and source of emission in horizontal direction (m)
y	distance between the center of hood face and source of emission in vertical direction (m)
α	direction of particle emitted from source (degree)
θ	hood orientation in terms of angle between centerline and horizontal line (degree)

Introduction

In 2003, the SARS outbreak killed 299 people and resulted in 1,755 infected patients in Hong Kong. In the health care sector, 386 health care workers (HCWs) in hospitals, clinics, and medical schools were infected and, unfortunately, 8 died. Evidence has shown that the main modes of SARS transmission are direct mucous membrane contact (eye, nose, and mouth) with infectious respiratory droplets and aerosolised respiratory secretions. The close contacts with SARS patients pose high risk of nosocomial infection to the HCWs who perform critical medical procedures, such as emergency endotracheal intubation. HCWs are suggested to take various infection control measures to avoid different modes of disease transmission. Some examples include wearing surgical masks and protection eyewear, spacing out patients, avoiding use of nebulisers, and minimising cough-inducing procedures. Equally important, effective environmental control by engineering devices is necessary for removal of droplets and aerosols generated by infectious patients. Local exhaust ventilation (LEV) has been identified as a potential solution. The objectives of this study are to design an effective LEV system by means of computational fluid dynamics (CFD) simulation and validate the performance by experimental tests of a prototype.

Local Exhaust Ventilation

Local exhaust ventilation (LEV) is used to remove contaminants (vapors and particulates) immediately at the source to avoid the spread in the air [1][2][3]. The extraction arm of a LEV system allows the hood to easily move to any position and orientation around the source for effective collection of the emission with little obstruction in the work space. In the industry, LEV is widely used to protect workers by exhausting chemical fume and dust in manufacturing processes, such as soldering, welding, grinding, polishing, etc. The engineering control method can also be applied effectively in a health care environment to protect HCWs against nosocomial infection. During bioaerosol-induced medical procedures, increases in ventilation and air change rate are simply insufficient to protect the HCW in close contact with an infectious patient. Alternatively, LEV can be used to draw droplets and aerosols away from the HCW and immediately remove them in the vicinity of the patient, as illustrated in Fig 1. The effectiveness of a LEV system depends on multiple factors, including hood size and shape, position, orientation, air flow rate, etc.

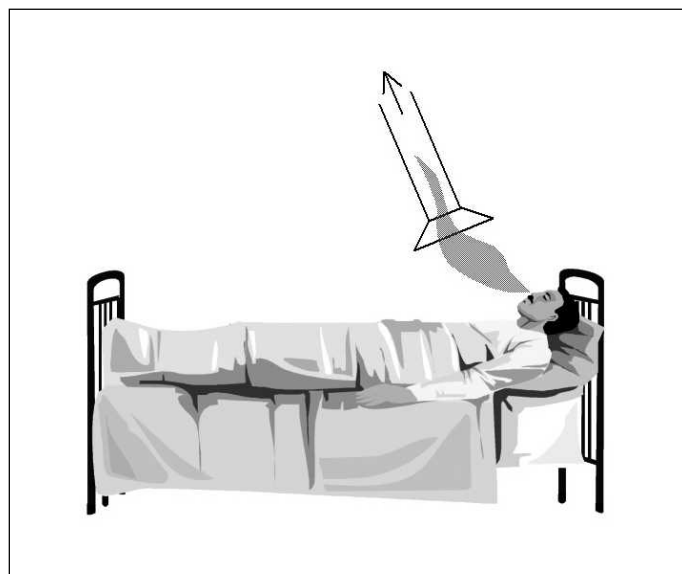


Figure 1 – Illustration of Local Exhaust Ventilation

Objective and Significance

The purpose of this study was to design a LEV system suitable for removal of droplets and aerosols to protect HCWs during bioaerosol-induced medical procedures. CFD analysis was employed to simulate the transport of particles in the airflow for design optimisation of extraction hood and LEV system. A prototype was built and tested for validation and evaluation. With further modification and improvement, the LEV system may become a significant engineering device for nosocomial infection control.

CFD Analysis

The CFD flow models we used here consisted of the Navier-Stokes and continuity equations. Steady-state incompressible flow was assumed in the calculations. The fluid turbulence was modeled by the standard $k-\epsilon$ turbulence model. While the fluid phase was modeled by the Eulerian approach, the droplets and aerosols were assumed to be transported in the form of particles of different sizes by the Lagrangian approach [4][5]. The turbulent dispersion of droplets and aerosols was modeled by the stochastic tracking model. The collision between particles and solid boundaries was assumed to be completely inelastic. Thus, in the modeling computation, particles would stick on solid boundaries after collisions and were then removed from the computational domain. Commercial CFD code FLUENT [6] was utilised to formulate the computational models to perform simulation and design optimisation.

Unstructured meshes were used to model the complicated flow geometry. After a grid independence test was conducted, it was found that about 300,000 triangular elements were sufficient to carry out the axisymmetric calculation in the design stage. More than 1,600,000 tetrahedral elements were adopted in the 3D calculation during hood performance evaluation. High spatial resolution was implemented to determine the airflow in the near-wall region within 2 mm from the wall boundary.

It is worth mentioning that, other than the $k-\epsilon$ turbulence model, the Reynolds stress turbulence mode had been considered to be adopted in this study. We found that specifications of the boundary conditions in terms of Reynolds stresses are required, however, the information in that regard is insufficient. It would induce inaccurate computational output and thus the $k-\epsilon$ turbulence model was used instead. Apart from inaccurate boundary conditions, the Reynolds stress turbulence model needs additional equations that would double the computational load on the already long calculation time.

In the CFD modeling, it was assumed that the airflow was isothermal. In other words, neither the body heat nor the warm air exhaled was considered. It was justified because the main concern was the relatively small spatial domain of the vicinity of the patient, health care worker, and local exhaust. Moreover, the problem was analysed for the critical conditions, such as sneezing and cough, in which the pollutant emissions were at a high speed. The buoyancy effect would be less significant.

Three particle sizes, 1, 10, and 50 μm in diameter, were employed in the CFD analysis. The mean particle diameter of aerosols or droplets emitted from patients is 10 μm (Kowalski and Bahnfleth 1998). CFD runs for particle of diameter 1 and 50 μm are sensitivity test to investigate the hood capture efficiency for a reasonable range of particle sizes.

Preliminary Design of Extraction Hood

The hood design is of particular importance as it changes the capture velocity and the flow pattern. In this study, 13 different hood configurations, as depicted in Fig 2, were analysed in the preliminary design stage. The conical (Types 1 through 5) and bowl-shape (Type 6) hoods were actually widely used in the industry, while the others were potential alternatives. Axisymmetric CFD analysis was conducted to evaluate the performance for each hood configuration. The criteria used to indicate high particle removal effectiveness were (1) high capture velocity, (2) short time taken to draw particles from source to hood, and (3) low degree of recirculation around and inside hood.

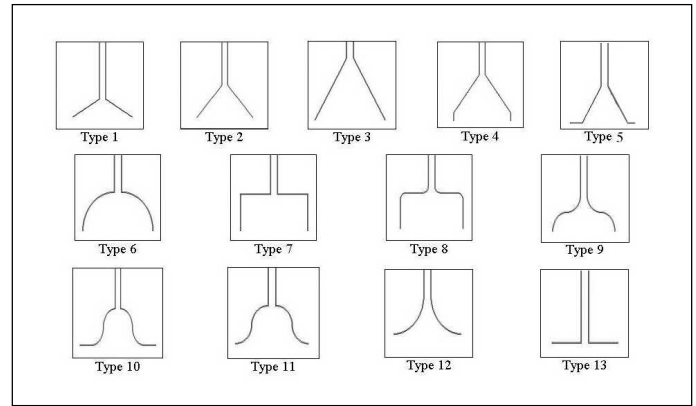


Figure 2 – Hood Configurations Tested in Preliminary Design Stage

Detailed Design of Extraction Hood

In the preliminary design, the horn-shape hood (Fig 2, Type 12) was found to be most effective. In the detailed design, the hood curvature was optimised for maximum particle capturing effectiveness. The design constraints were primarily the hood dimensions. HCWs recommended that the hood diameter should not exceed 300 mm; otherwise, it would obstruct the work space for normal operation. The diameter of the extraction arm was sized to 160 mm for a maximum air flow rate of 0.36 m^3/s .

The detailed design was accomplished by an axisymmetric CFD analysis in the domain with boundary conditions described in Fig 3. For each hood curvature tested, 50,000 simulations, each calculated the transport of a single particle, were conducted and evaluated. The simulations covered various particle sizes of 1, 10, and 50 μm with different initial particle emission velocities (Table 1). The curvature resulting in maximum number of particles successfully captured by LEV was selected as the optimal curvature.

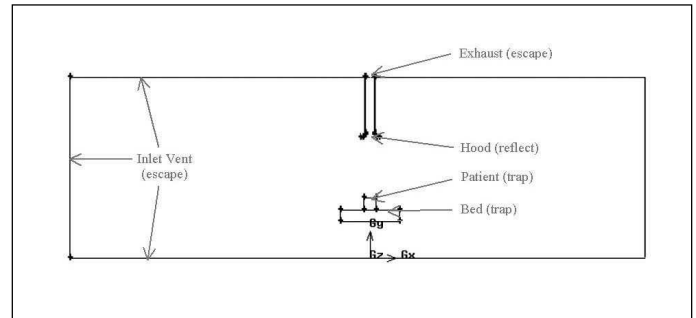


Figure 3 – CFD Domain for Hood Optimisation Analysis

No	Particle speed, V_p (m/s)	Direction, α (degree)
1	0.0	–
2	17.9	90° (vertical)
3	17.9	45°
4	17.9	0° (horizontal)

Table 1 – Initial Velocity of the Particle Emitted in Simulation for Hood Optimisation

3-D CFD modeling

A 3-D CFD model was set up (Fig 4) to simulate the operation of the LEV system in a hospital environment. The patient ward model sized 6.7 m (long) x 6 m (wide) x 2.7 m (high) consisted of 1 HCW and 1 patient lying on bed. The hood was 0.424 m away from the patient's head ($x = 0.3$ m, $y = 0.3$ m). The air speed in the LEV extraction arm was 15 m/s (equivalent to volumetric air flow rate of 0.3 m^3/s). The CFD

simulations were conducted based on the following conditions (1) negligible ventilation in the patient ward, (2) make-up air entering the room through the door undercut, and (3) initial particle emission velocity (Table 2). By using the particle tracking method, the paths of 10,000 particles emitted were determined. The number of particles hitting the HCW's head were then counted.

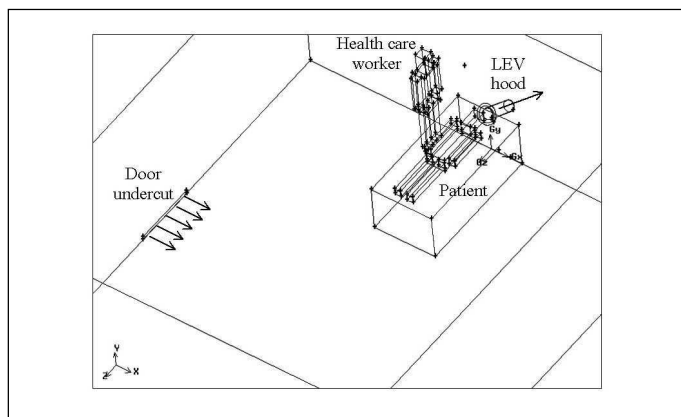


Figure 4 – 3-D Modeling of LEV Operation in Patient Ward

No	Particle Speed, V_p (m/s)	Direction, α (degree)
1	100	-90° (towards HCW)
2	100	-45°
3	100	0° (upwards)
4	100	45°
5	100	90° (away from HCW)

Note: When one is sneezing, the average speed of droplets is 100 m/s [7]

Table 2 – Particle Velocity Tested in 3-D CFD Modeling

Experimental Study

Visualisation Test

A LEV prototype as shown in Fig 5 was built. Its performance in a smoke test was first conducted in a chamber sized 6.7 m (long) x 6 m (wide) x 2.7 m (high) (Fig 6). Visible particles were generated by a fog generator (Model Jem'zr 33) and stored in a large bottle at room temperature. The smoke was then uniformly released through the mouth of a manikin with built-in artificial body heat. Various hood positions and orientations were tested (Table 5). A digital video camera was used to record the flow for careful examination.

Aerosol Test

Quantitative study was conducted by aerosol measurements. The setup is shown in Fig 7. A TSI model 3400A fluidised bed aerosol generator

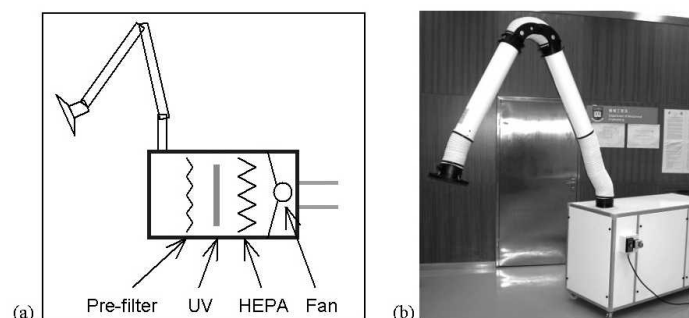


Figure 5 – LEV Prototype: (a) Schematic and (b) Photograph



Figure 6 – Test Chamber and Manikins Modeling a Hospital Ward

was used to produce respirable aerosols (median diameter = 10 μm) in the test chamber. The standard Arizona test dust was used as the test aerosols. A GRIMM Portable Dust Monitor Model 1.18 was positioned where the head of a HCW should be ($x = 0.3$ m, $y = 0.3$ m, opposite side of LEV) to measure the particle counts. As described in Table 3, the background concentration was first measured and, subsequently, the aerosol generator and LEV prototype were switched on and off in preset order.

After testing the LEV under laboratory conditions, the prototype was sent to a hospital in Hong Kong for a field test in an actual health care environment where the HVAC system was operating in normal condition. The test procedures were similar to those of the aerosol test discussed above. Moreover, feedback concerning the LEV operation was collected from the frontline HCWs.

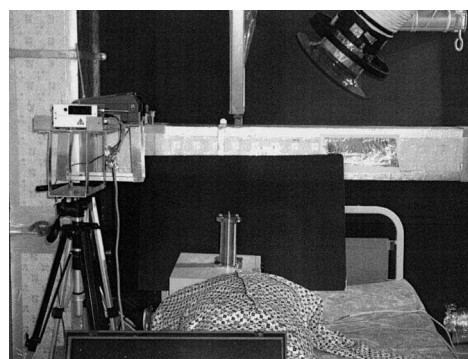


Figure 7 – Aerosol Test Setup

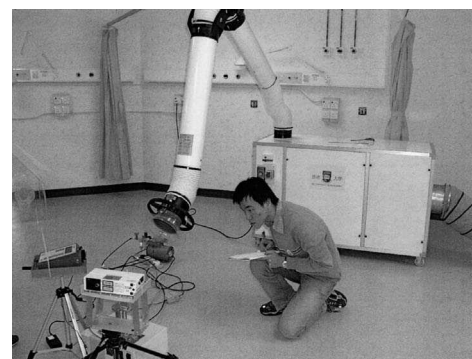


Figure 8 – Field Test setup in a Hospital

Step	Aerosol Generation	LEV Operation
1	Off	Off
2	On	Off
3	On	On
4	Off	On

Table 3 – Aerosol Test Procedures

Results and Discussions

Preliminary Design of Hood

In the preliminary design stage, the streamlines of airflow in the 13 different hood configurations (Fig 2) were obtained by CFD simulations. The streamlines of hood types 6, 12, and 13 are selected for illustrations as plotted in Fig 9. In Fig 9 a, a region of vigorous mixing and recirculation or a wake occurs near the entrance of the bowl-shape hood. As the wake causes ineffective removal of contaminants, the bowl-shape option is eliminated. By careful inspection, the horn-shape configuration (Type 12) is most unlikely to cause wake because the streamlines are smooth with little radical change.

As shown in Fig 10, along a contour of constant capture velocity of 0.5 m/s, the height to hood diameter ratio (H/D) and width to hood diameter ratio (W/D) indicate the zone coverage protected by the LEV system. Particle capture time is also an important measure of hood performance. Short particle capture time represents that aerosols are removed quickly and effectively. The CFD numerical and qualitative analyses are summarised in Table 4. Based on the comparisons of the velocity contours, particle capture times, and presence of recirculation, horn-shape hood (Type 12) is identified as the most promising design and selected for subsequent detailed design optimisation.

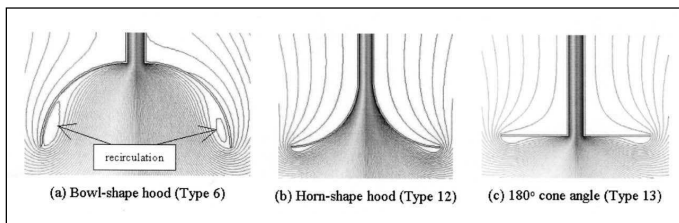


Figure 9 – Streamlines of Airflow Around Hood

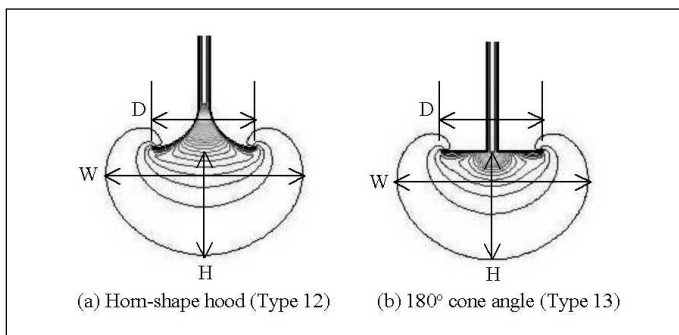


Figure 10 – Velocity Contours

Type	Velocity contour at $V = 0.05U$		Ranking in particle capture time	Presence of recirculation
	H/D	W/D		
1	1.05	1.95	4	No
2	1.03	1.95	10	Yes
3	1.03	1.98	5	Yes
4	1.03	1.98	11	Yes
5	1.05	1.93	7	No
6	0.90	1.85	13	Yes
7	1.05	2.03	6	Yes
8	1.03	1.95	9	Yes
9	1.05	1.95	8	Yes
10	1.08	1.90	2	No
11	1.05	1.95	12	No
12	1.05	1.95	3	No
13	1.10	1.85	1	No

Note: U is air speed of 10 m/s inside the LEV extraction arm.

Table 4 – Evaluation of Various Hood Configurations

Design Optimisation

In the detailed design stage, the objective is to determine the precise curvature of a horn-shape hood configuration for optimal LEV performance. Nine different curvatures (Indices A through I), as shown in Fig 11, were tested with three different particle sizes (1, 10, and 50 μm). The results are shown in Fig 12. Hoods C, D, E, and F show slightly better performance as they remove more particles than the others. Over the full range of test conditions, Type C performs consistently well. Thus, it is selected as the final design.

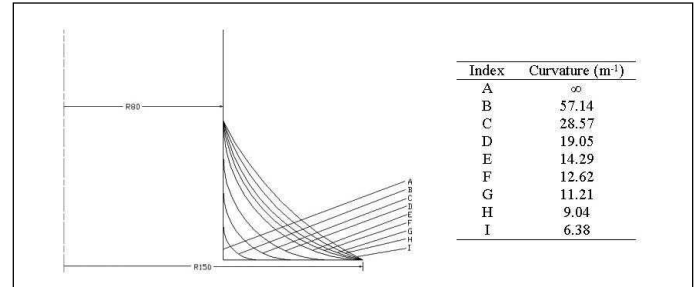


Figure 11 – Dimensions of Horn-shape Hood Tested

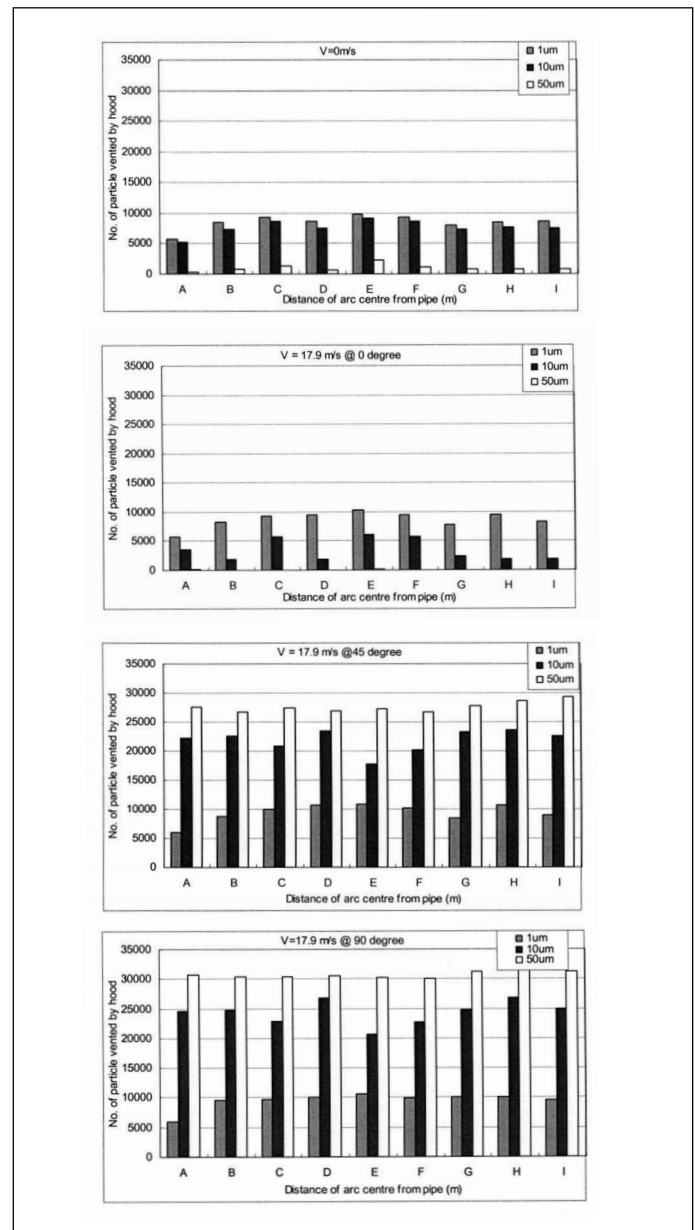


Figure 12 – Comparisons among Horn-shape Hoods of Various Curvatures

3-D Modeling of Patient Room

In the 3-D model described in Fig 4, the transport of each particle emitted by the patient was simulated. Without the operation of LEV, the numbers of particles that hit the head of the HCW are summarised in Table 5. The worst case occurs at $\alpha = 0^\circ$ and $d_p = 10 \mu\text{m}$ resulting in total 54 hits out of 10,000 particles emitted. When LEV is operated at an airflow of $0.3 \text{ m}^3/\text{s}$, equivalent to an air speed of 15 m/s inside the extraction arm, the simulations show zero hit on the HCW's head. The results indicate that the LEV operation provide sufficient protection for the HCW.

No	Particle emission		No of particles hitting HCW's head		
	Speed (m/s)	Direction, α (degree)	$d_p = 1 \mu\text{m}$	$d_p = 10 \mu\text{m}$	$d_p = 50 \mu\text{m}$
1	100	-90	9	9	16
2	100	-45	18	43	38
3	100	0	13	54	51
4	100	45	6	34	21
5	100	90	17	7	7

Note: d_p is the diameter of particle.

Table 5 – Results of 3-D Modeling of LEV

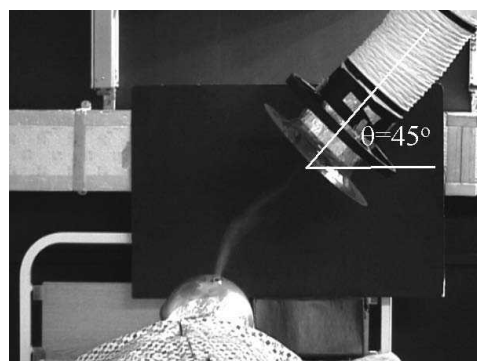
Visualisation Test Results

The LEV prototype was tested with various positions and orientations with respect to the manikin. When the hood was placed 1m away from the manikin and operated at an airflow of $0.3 \text{ m}^3/\text{s}$, the fog particles showed that the flow was unsteady and the LEV prototype collected only some particles emitted. As the hood was moved closer to the manikin, as expected, the LEV performance was improved.

Two examples, shown in Fig 13, are selected for further discussion. In Fig 13 a, it was assumed that a HCW was performing medical procedure on the right-hand-side of the patient (manikin). In order to protect the HCW, the LEV hood was placed on the opposite side at the same level of the manikin to draw the patient's emissions away from the HCW. It



a Hood Position
 $x = 0.3 \text{ m}$, $y = 0 \text{ m}$;
Orientation $\theta = 0^\circ$



b Hood Position
 $x = 0.3 \text{ m}$, $y = 0.3 \text{ m}$;
Orientation $\theta = 45^\circ$

Figure 13 – Flow Visualisation of LEV

then captured and exhausted the emissions to the outdoor environment. In Fig 13 b, the hood was moved to a higher position at $y = 0.3 \text{ m}$. The visible flow in both tests showed 100% capture of the particles emitted.

Aerosol Test Results

The results of one of the aerosol tests with LEV (hood position $x = 0.3 \text{ m}$, $y = 0.3 \text{ m}$ and orientation $\theta = 45^\circ$) are plotted in Fig 14. The starting of LEV quickly reduced the particles of $d_p > 0.4 \mu\text{m}$ from 12,000 to 8,000 particles per liter, and particles of $d_p > 10 \mu\text{m}$ from 4,500 to 1,900 particles per liter in about 10 seconds. Subsequently, the particle concentration gradually reduced towards the original background level. The field results plotted in Fig 15 exhibit similar particle capturing performance.

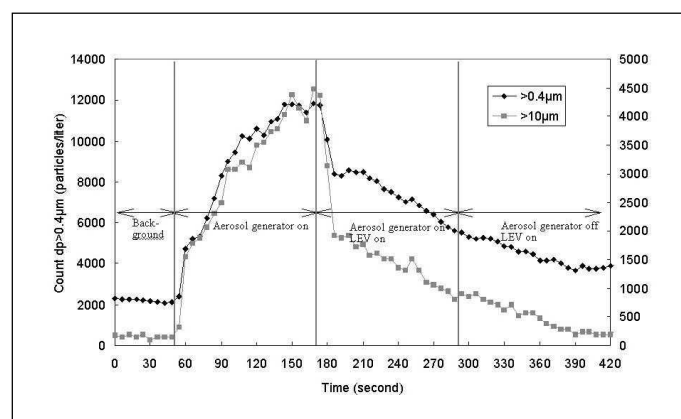


Figure 14 – Performance of LEV in Laboratory Test

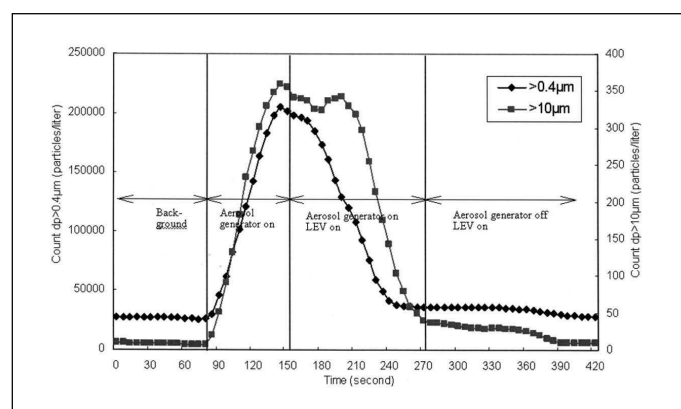


Figure 15 – Performance of LEV in Field Test

Conclusions

CFD analysis and empirical investigation have been conducted to design and evaluate LEV for nosocomial infection control. It is concluded that the hood shape profile can influence the airflow performance. A smooth velocity profile without recirculation yields a better capturing effectiveness. Among the configurations tested in this study, horn-shape hood is preferred. The capture efficiency of the hood varies with particle sizes and its operation orientation. Placing the hood above the patient or offset with a 45° angle measured from the horizontal axis exhibits a higher capture efficiency for a wide range of particle sizes. According to the feedback collected from the frontline HCWs, the LEV prototype tested in this study is too big for some hospital wards. The LEV system will be modified to make it more compact.

Acknowledgements

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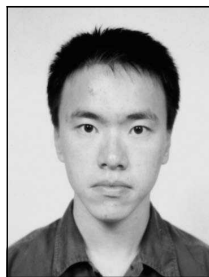
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