Analysis of Air and Airborne Particles Movements in a Hospital Operating Theater

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Abstract. In this study a computational fluid dynamics (CFD) method was used to develop a validated model of a hospital operating theater. The model was employed to perform simulation to predict the distribution of airflow and movement of the airborne particles inside the operating theater at a steady-state condition. The airborne particles were modeled as discrete particles which were released from the exposed body surface of the surgical staffs at a rate of 10 CFU/s. The effect of laminar inlet air flow velocity on the airborne particles concentration around the operating table was examined. It was found that the air flows straight downward from the air-conditioning diffuser towards the middle of the operating table. However, the existence of the medical lamp causes a vortex air flow condition below it. Air also penetrates the ultra-clean area on the opposite side of the operating table. The airborne particles are washed away from the vicinity of the operating table by the air flow. This is more effective when the supply air flow velocity is high. At low air flow velocity, some particles appear to penetrate into the ultra-clean area near the edges of the operating table. At higher air flow velocity, the airborne particles seem to be more effectively washed away from this region. High concentration of airborne particles occurs underneath the medical lamp due to vortices created by the air flow. Higher air flow velocity increases the level of particles concentration in this area.

Introduction

An operating theater of a hospital is a dedicated place for patients to undergo surgeries. Improper design of the theater might cause patients to get post-operative illnesses or nosocomial infections. This can be caused by various sources ranging from surface contaminants to airborne particles contaminant. Studies have found that 80-90% of the contaminations found in the open wound were from the airborne particles. Hence cleaner air would guarantee lesser cases of nosocomial infections [1].There have been extensive studies made on hospital acquired infection (HAI) lately. Hospitals worldwide are facing huge annual losses in terms of financial and lives of the patients due to HAI. Nosocomial infections, besides bringing misery to the patients, also incur huge amount of financial losses for the healthcare service providers. In Malaysia, the incidence of HAI was reported to be 13.9 % of all the hospital related infections. A significant portion of HAI in Malaysia was due to surgical site infections (SSI), which accounts for 23 % of all the reported HAIs. Malaysian hospitals suffer estimated annual losses of 3.25 million additional bed days in addition to the financial losses amounting toRM340 million due to the SSI. Mortality rate due to HAI was reported to be in the range of 3-5 % [2].

Researches on HAI and clean room configuration of operating theatre have been ongoing since 1960s. These researches were aimed at trying to achieve better airborne contaminants removal strategies to improve safety for the patients and healthcare workers and to help reduce financial losses. Proper ventilation system is important in removing contaminants from important parts of the patient's body during operation. Following the advancement of computing processor power today, the task of studying the air flow and contamination concentration can be done by computer simulations. Previous researches have shown that numerical analysis is capable of providing accurate results that are comparable to field measurement [3-5].

This article presents a study to predict air flow distribution and movement of airborne particles inside a hospital operating theater using a computational fluid dynamics (CFD) method. A CFD model was developed and used to simulate and predict the airflow distribution and airborne particles movement inside the operating theatre at a steady-state condition. The contaminants were modeled as discrete particles that are released from the surgical staff's body surface at a rate of 10 CFU/s. This value was obtained from the literature. The effect of laminar air flow inlet air velocity on the airborne particles concentration around the operating table was examined.

Ventilation System for Operating Theater. The primary purposes of a ventilation system for the operating theatre is to control the temperature and humidity of the air, to remove and dilute anesthetic gases, to wash out airborne contaminants and to regulate the air movement so that the transport of airborne bacteria to the ultra-clean area is minimized[6]. Thus important parameters that need to be considered in designing the ventilation system are the ventilation effectiveness, pressure differential between the various sections of the operating theater and the supply air velocity and its temperature. Other aspects of the operating theatre must also be considered in selecting the suitable ventilation system, specifically the height of the operation theatre. There are 2 major types of ventilation systems used in operating theatres. Most commonly used system is the mixed flow ventilation system. This system is capable of diluting the airborne bacteria in the air by providing sufficient amount of clean air into the operating theater space. The use of such system would results in a uniform level of air contaminants concentration throughout the operating theater space. A displacement ventilation system would provide clean air that is directed to the ultra-clean area only. The level of contaminant concentration inside the theater is therefore not uniform.

There are no specific guidelines by any organization on the type of ventilation to be used in the operating theatres. Many hospitals worldwide are using the laminar air flow (LAF) displacement ventilation system with high efficiency particulate (HEPA) filter that is able to filter out particles of up to 3µm in size and providing clean air to wash out the contaminants from the ultra-clean area (i.e. the operating table). Studies have shown that the size of the ventilation system needs a special consideration. A bigger system is better as it can cover the entire operating table area but this is difficult to achieve due to the high fresh air volume required. If the size of the system is too small, the air flow would be turbulence and this would reduce the particle free protection zone [7]. It must be noted that even a good ventilation system may not work perfectly since there are various factors that may affect the air flow distribution. Some of the important factors include the medical lamp position and the existence of a partition wall. Chow et al. [8] has shown that the lamp position has strong influence on the ventilation system performance in washing off the airborne particles. They also found that excluding partition wall in the configuration exposes the patient to a dangerous level of particle concentration due to infiltration of contaminated air into the ultra-clean area [9].

CFD Analysis on Operating Theatres. There are many studies reported in the literatures on the use of computational fluid dynamics (CFD) method to simulate air flow in operating theatres. Chow [8] conducted a study on laminar air flow in a standard operation theatre in Hong Kong using CFX 4.3 software. In this work, he varied the inlet air velocity, change the position of medical lamps, and the magnitude of heat flux from the medical lamps to investigate how these factors affect the air flow pattern and distribution of the airborne particle concentration. He found that air velocity pattern is an important factor in the dispersion of airborne particles. He also found that, higher air flow velocity was able to dissipate heat generated by the medical lamp more effectively. Also, the phenomenon of thermal plume was low compared to a lower air flow velocity condition.

The existence of a partial wall would block a contaminated air from entering the path of clean air flow. The medical lamp will deflect the flow of clean air from the LAF diffuser into the ultra-clean area where the patient is lying. Zhang [4] reported that the air flow pattern affects the distribution of the airborne particle concentration. Increasing the air flow velocity beyond certain level would increase the airborne particle concentration in the ultra-clean area (i.e. the surgical table). His study was validated using data obtained from field measurement using bacteria collecting agar dishes that he claimed to be quite accurate.

Infection Control Guidelines in Malaysia. Malaysia has its own policies and procedures on infection control set by the Ministry of Health which underlines the requirements to be fulfilled by all health care providers. The policies cover various aspects of infection control including the management, general practices and procedures and technical. As on the ventilation system for the operating theatres, there is only a guideline on the allowable limits of microbiological air contaminants inside the theater is as given in Table 1. However, this guideline does not provide specific guidelines on how to reduce the infection rate on the patients. Nevertheless it can be used as a reference on the acceptable limit of the air contaminants around the operating table. The Hospital Infection and Antibiotic Control Committee (HIACC) have also developed policies and procedures related to the infection control and usage of antibiotics for reducing the cases of Healthcare Acquired Infection (HAI) in Malaysian hospitals. The committee also advises hospital directors on the technical matters related to infection control in their hospitals [10].

Table 1 Guideline on the level of air contaminants in operating theater (Ministry of Health Malaysia, 2010)

Description	Ultra Clean Air
Microbiological count when:	
i) Empty	< 1 CFU/m^3
ii) In Use	<10 CFU/m^3 (Over the operating table)
	< 20 CFU/m^3 (Corners of the room)

Source of Air Contamination in Operating Theater. In a typical operating theatre, the main source of contaminants is from the healthcare workers due to their activities. Liu *et. al.* [5] stated that main source of bacteria are the skin flakes or other contaminated particles having diameter in the range of 5 - 10µm. These particles generally have a density of 2 g/cm^3. In Zhang *et. al.* [4] analysis, release rate of 200 bacteria colonies/minute for upper body and 400 bacteria colonies/minute in the lower part of the body was used for a total of 600 bacteria colonies/minute/staff. No particles were released from the patient. Diameter of particle selected was 6µm as there is no significant difference in the deposition result. Other researcher stated that a surgeon during surgery is a source equivalent to as many as 1000 airborne particles/min [11]. The difference in particles release rate may be due the type of clothing worn by the surgeon and the safe practices adopted by them. Air contaminants from the inlet air is considered negligible due to the use of High Efficiency Particulate Air (HEPA) filters that are able to filter out particles of more than 0.3µm in diameter [5].

Heat Sources in Operating Theatre. There are many heat sources in the operation theatre: the medical equipments, lamps and the surgical staffs who are working during the operation. Heat creates a buoyancy driven-airflow that flows upwards [5]. Depending on the temperature difference, supply air velocity and the heat generation rate, it may disrupt the air flow pattern in the operating theatre. The magnitude of heat generated from medical equipments and lamps can be obtained from the specification of the equipments. Equipments such as the main medical lamp and the satellite medical lamp release heat at a rate of approximately 350 W and 200 W, respectively. Surgical staffs and patient release heat in the range of 100 to 150 W.

Many researchers did not consider the surgical staffs and patient as heat sources because they claim that the simplified model of them has less surface area than the actual body area. Also, by considering them as heat source would produce a high localized temperature around the people's model [4]. One researcher however did use simplified heat sources to suit the operating theatre model known as computer simulated persons (CSP). The patient usually produces the least amount of heat while the surgeon generates the highest amount of heat. The heat supply in the form of heat flux may be more accurate compared to heat generated from the model surface.

Materials and Method

Model of the Operating Theatre. In this study, a general purpose computational fluid dynamics (CFD) software ANSYS Fluent was used to develop a simplified model of a typical hospital operating theatre. The theatre is 7.8 m long, 6.6 m wide and 3 m in height. The model comprises of an operating table placed in the middle section of the theatre. Also included are four surgical staffs, two on each side of the operating table. They are represented by slender cylindrical geometries having a diameter of 0.3 m and height of 1.75 m, as typically used in many previous studies reported in the literatures. A medical lamp is also included into the model, which is located above one end of the operating table. The lamp is inclined at a 45° angle from a horizontal position. These are shown in Figure 1. As seen from this figure a laminar air flow (LAF) supply diffuser measuring 2.2 m x 2.2 m is located on the ceiling directly above the operating table. Two exhaust outlets measuring 0.5 m x 0.5 m are located on the opposite side walls near the bottom of the walls.

CFD Simulation. To perform the simulation, the interior space of the CFD model was first discretized or subdivided into smaller parts called elements. In this study, three-dimensional tetrahedral elements were used. Each element has a total of eight nodes and there are four degrees of freedom at each node. These are the velocity components in the *x, y*, and *z* directions, and pressure. A total of 246000 elements were used in this study. This number was obtained through a mesh sensitivity study to eliminate the effects of number of elements on the results of the CFD simulation. Air was supplied from the laminar air flow (LAF) diffuser located on the ceiling of the operating theatre above the operating table. The air was treated as behaving like a perfect gas. In addition, the flow of the air was considered to be incompressible and at a steady-state condition.

An air flow boundary condition was prescribed at the LAF diffuser to model the supply of clean air into the operating theatre. In the base case simulation, the velocity of the air was specified at 0.11 m/s. A zero pressure state was prescribed on the two exhaust outlets on the walls of the operating theatre. This represents an atmospheric pressure condition that exist the two outlets. A no-slip flow condition was prescribed on all the walls of the operating theatre. This type of wall condition would simplify the CFD analysis as the tangential component of the air flow velocity is neglected during the computation. Other parameters used during the CFD simulation are shown in Table 2. The values for these were taken from the literatures [4, 5, 12].

A pressure-based solver was chosen for the CFD flow analysis. The air velocity formulation was selected as absolute with the time specified as steady. The gravity effect was not considered in the analysis for simplification. Heat transfer analysis was turned-on by activating the energy equation feature. This will ensure that the effect of heat dissipated from the surgical lamp and staffs would be taken into account during the computation. A standard *k-e* realizable turbulent model was chosen for the viscous flow analysis. This flow model is generally known to be accurate for a simple flow analysis in an enclosed region. It was used in many studies as reported in the literatures.

A standard wall function was used for the near wall flow condition. A 5% turbulent intensity was selected for the CFD analysis.

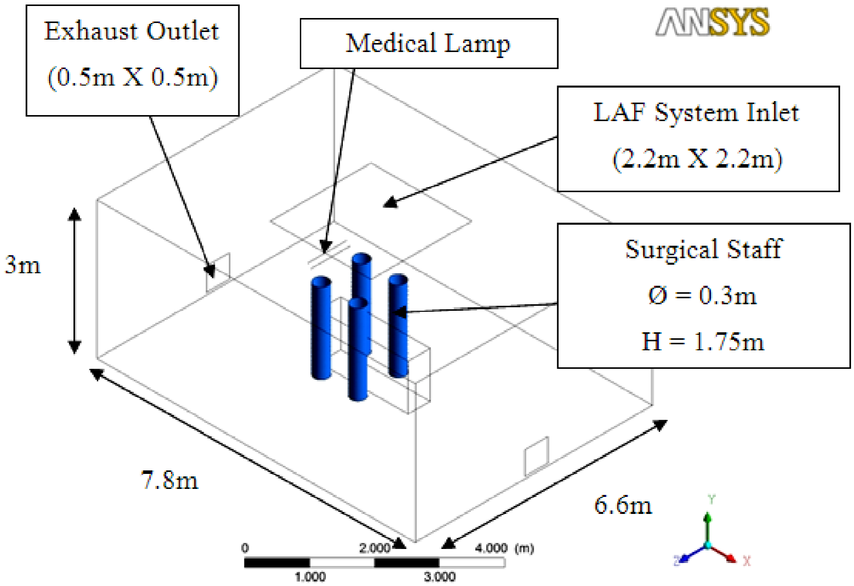
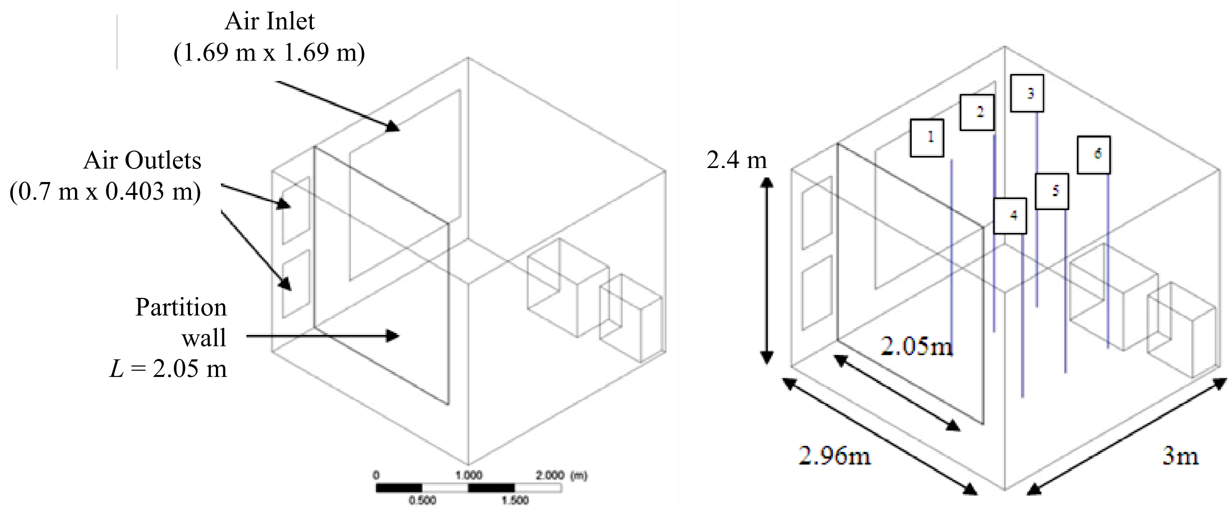


Figure 1 Simplified CFD model of the operating theatre.

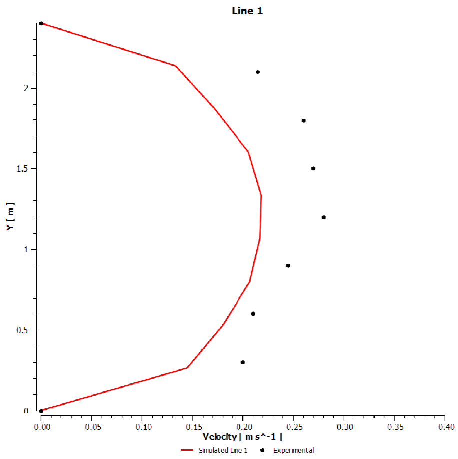
A discrete particle model option was used to model the movement of the airborne particles in the operating theatre. This option allows the CFD analysis to predict the movement trajectory of the particles resulting from the air flow pattern. In this study the airborne particles were assumed to be released from the exposed surfaces of the surgical staffs. Based on our calculation, the particles were released at a rate of approximately 1.31 x 10^{-12} kg/s from each surgical staff (see Table 2).

Validation of the CFD Model. The CFD model we developed in this study was validated to ensure it will produce results that are reliable. We carried out the validation by referring to the work reported by Liu [5]. We developed the CFD model of the operating theatre similar to the one used by the author in his study. This is shown schematically in Figure 2. The same CFD analysis setup was employed for the simulation, as described previously. Our results on air flow velocity profile along six vertical path lines were compared graphically with the experimental results reported by Liu [5].

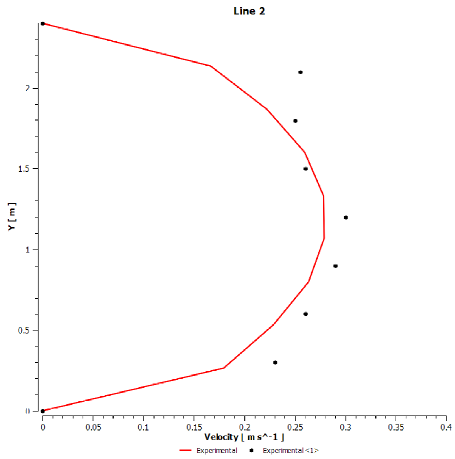


(a) Geometry of the operating theatre. (b) Path lines for air velocity data.

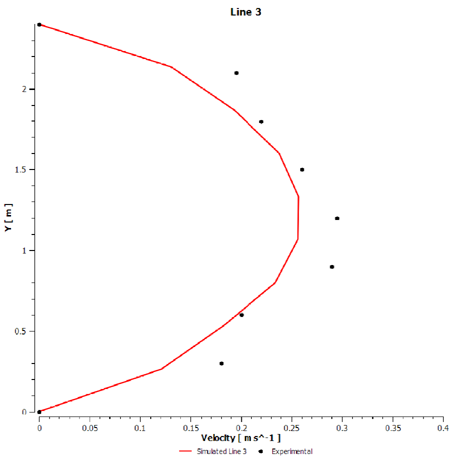
Figure 2 CFD model of the operating theatre used for validation.



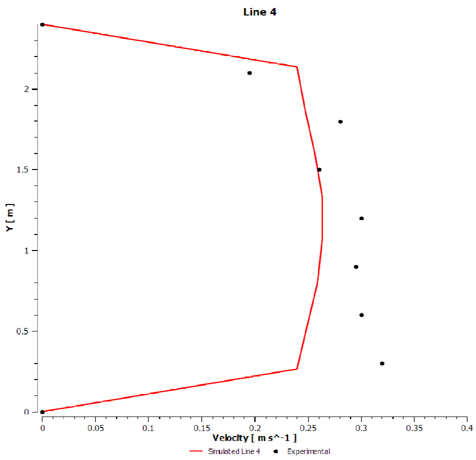
(a) Along path line no. 1



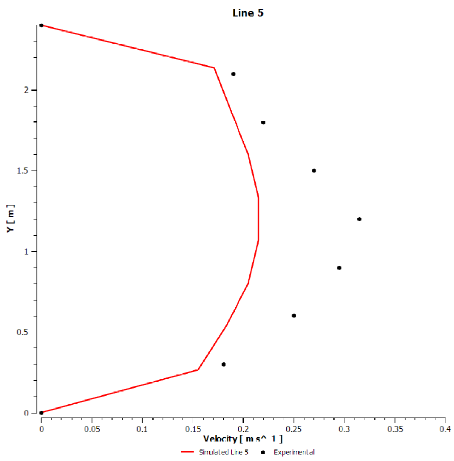
(b) Along path line no. 2



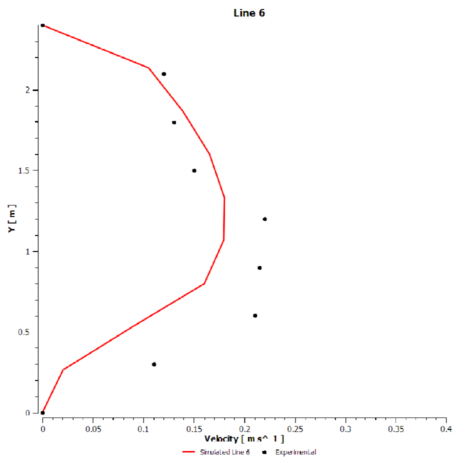
(c) Along path line no. 3



(d) Along path line no. 4



(e) Along path line no. 5



(f) Along path line no. 6

Figure 3 Comparison of velocity profile for validation of CFD model.

Figure 3(a) through 3(f) show the plots of air velocity profile (represented by solid lines) along the six path lines shown in Figure 2(b), obtained from the CFD simulations. The velocity profiles are compared to the results reported by Liu [5] (represented by the dots) along the same path lines. It can be observed that although the solid lines do not exactly trace the dots in all the figures, but the trend of the air velocity variation along each path line appears to agree quite well. The difference between our simulation results and the experimental data by Liu [5] could possibly due to numerical error involved in our CFD simulations. We therefore conclude that the CFD model and simulation set up we developed in this study is valid to be used in the proceeding analysis.

Parametric Study. In this study we also investigated the effects of different air flow velocity at the LAF diffuser on the air flow pattern and the distribution of the airborne particles concentration in the vicinity of the operating table. The same CFD model described earlier (Figure 1) was employed in this parametric study. A similar turbulent flow model and analysis were also used. The different values of air flow velocity at the LAF diffuser we considered in this parametric study are shown in Table 3.

Table 2 Parameters used for a parametric study.

Parameter	**Value**
Inlet air temperature	293 K
Staff heat flux	30 W/m^2
Medical lamp heat flux	250 W/m^2
Particle diameter, Ø	5 μm
Particle density	2 g/cm^3
Total particle release flow rate from 4 staffs surfaces	5.24 X 10^{-12} kg/s
Calculation of Particle Release Rate Volume of particle, $V = \pi r^3 = 6.54 \times 10^{-17}$ m^3. Mass of each particle = $\rho \times V = 1.31 \times 10^{-13}$ kg. CFU release rate per staff = 600 CFU/Min = 10 cfu/s. Mass flow rate of particles = $\rho \times V \times$ CFU/s = 1.31×10^{-12} kg/s/staff.	

Table 3 Air flow velocities considered for a parametric study.

Case	**Air Inlet Velocity (m/s)**
1 (base case)	0.11
2	0.18
3	0.35

Results and Discussion

Air Flow Pattern. Air flow pattern would have a strong influence on the movement of the airborne particles within the operating theatre. The air flow should promote the movement of airborne particles and bacteria that are released from the surgical staffs and possibly the medical equipments, away from the ultra-clean area i.e. the operating table. The particles should move towards the exhaust outlets and eventually leave the operating theater. This is to ensure that the patient could be prevented from possible infections during the surgical procedure.

The results obtained from the CFD simulation for a base case in which the air supply velocity is 0.11 m/s is shown in Figure 5. This figure shows a two-dimensional plot of velocity vectors, which indicate the pattern of air flow inside the operating theatre, on a symmetrical vertical plane, shown in Figure 4. It can be observed from this figure that the air from the LAF diffuser moves downward towards the operating table in a fairly uniform condition. The presence of the medical lamp causes the air flow to be deflected to the left side of the plane. This creates a region of slightly lower pressure underneath the lamp. This in turn causes the surrounding air to flow towards this region thereby creating a vortex air flow condition above the operating table area. This is an undesirable condition as it can promote the inflow of airborne particles into this region.

The air flow is also deflected as it hits the edges of the operating table. This causes the airflow to change its direction and the air moves towards the exhaust outlets located on both sides of the plane. This will cause the air contaminants to be removed from the vicinity of the operating table and exhausted from the operating theatre. It can also be seen from the figure that there is an inflow of air into the area of the operating table on the right side of the plane. This appears to be the air that is deflected from the sidewall and the ceiling of the theatre. This is not a desirable condition as it can cause the influx of air contaminants into this ultra-clean area.

It was found that all the three cases as shown in Table 3 give results that exhibit the same airflow pattern. The clean air goes to the critical operation table area, before escaping through the exhaust outlets on the wall. The ingression of possibly contaminated air into the path of clean airflow also occurs in all the three cases due to the circulation of air near the corners of the operating theatre. This could cause some airborne particles to be carried into the ultra-clean area thereby increasing the level of contaminant concentration there. This situation agrees quite well with results reported by Chow and Yang [9]. They showed that without a partial wall around the LAF inlet, the concentration of contaminants is higher around the critical area due to the ingression of contaminated air.

Airborne Particles Flow Pattern. The flow patterns of the airborne particles obtained from the CFD simulations are shown in Figure 6 and Figure 7, respectively. The path lines shown in these figures represent the traces of the airborne particles movement, which originates from the surgical staffs surface towards the exhaust outlets located near the bottom of the side walls.

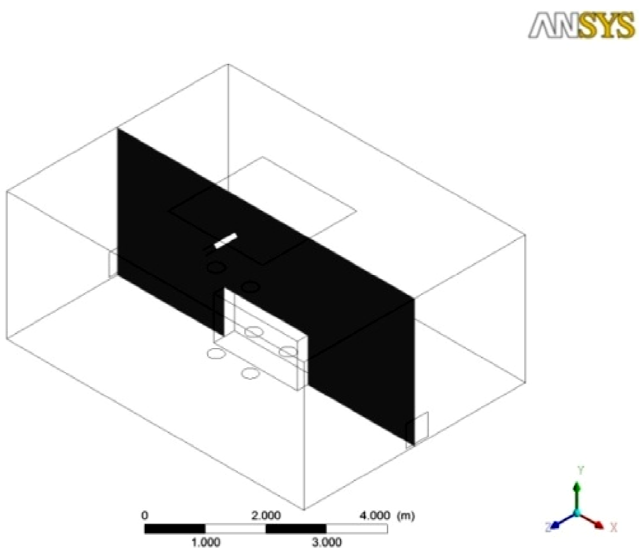


Figure 4 Plane *XY* at a position *Z*=0.235m.

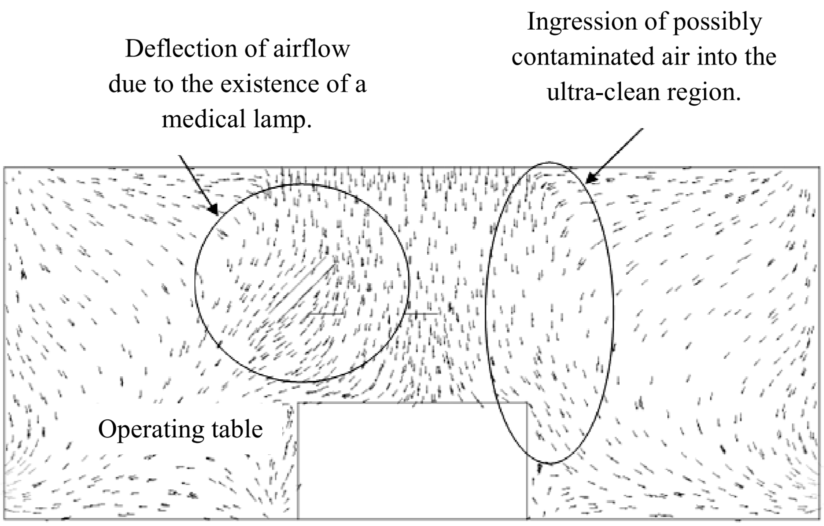


Figure 5 Velocity vector on *XY* plane (V_{inlet} = 0.35m/s).

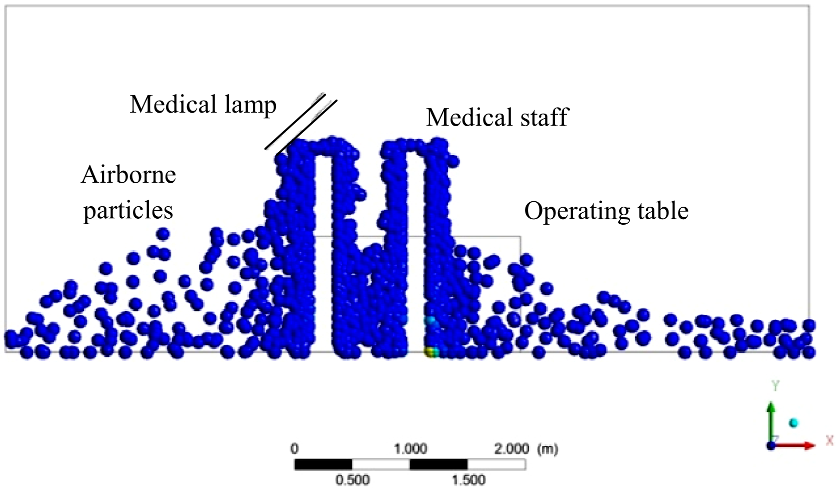


Figure 6 Airborne particles flow pattern on the *Z*-Plane shown in Figure 4.

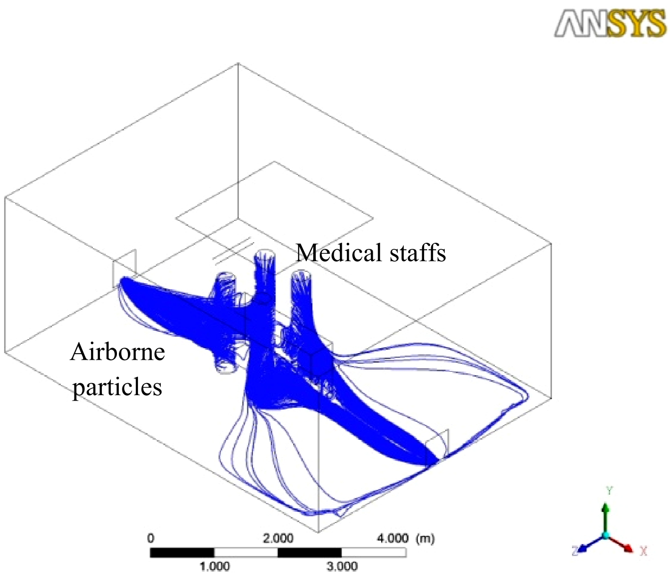


Figure 7 Isometric view of the airborne particles flow pattern.

It can be seen from the figures that the airborne particles are “washed” away by the air flow, i.e. they are driven by the air flow towards the exhaust outlets. However, the airborne particle concentration seems to be a tad higher on the left side of Figure 6. This could be due to the inwards air flow condition that occurs in this area that accumulates the airborne particles into the area, underneath the medical lamp. From Figure 7, it can be seen that airborne particles appear to have penetrated into the ultra-clean area, i.e. above the operating table. This could be due to the high velocity of air flow in the vicinity of the surgical staffs that are “standing” close to the operating table. This is obviously an undesirable situation during the actual surgical procedures. One way of preventing this situation is perhaps through the use of air curtain. The air curtain systems utilize two distinct types of air movement, downward laminar flow above, or nearly above the patient, with a perimeter of higher velocity air forming a 'curtain' outside the sterile field or surgical staff. The laminar flow comes from LAF air supply diffuser. The perimeter air curtain is usually supplied through a specially designed slot, or arrangement of slots. These are specially designed because the air curtain must have lower air velocity than a slot diffuser used for general ventilation purposes. These two flows should be designed to have a specific mass or velocity ratio.

Airborne Particles Concentration. Figure 9 through Figure 11 show the variation of airborne particles concentration on a horizontal plane, at a height of 1 m from the floor (Figure 8), for the three different cases of airflow velocity (Table 4). This plane is exactly flushed with the top of the operating table on which the patient is located during the surgery.

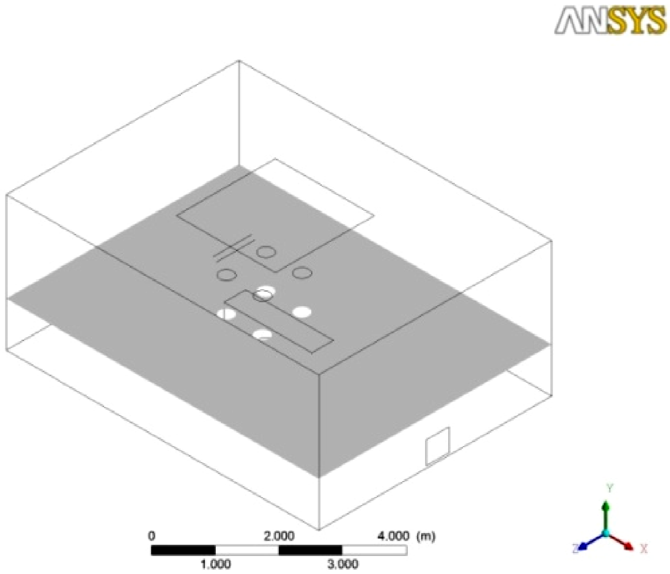


Figure 8 Plane *XZ* at position *Y* = 1.0 m from the floor.

The minimum value of particle concentration shown in the figures is 10 CFU/m^3 (1.31 x 10^{-13} kg/CFU), which the safe limit of air contaminants over the operating table, as specified by the Malaysia’s Ministry of Health Guideline on Operation Theatre [10]. As seen from the figures, the area to the right of the operating table shows an airborne particle concentration level that is higher than the safe limit. This occurs for all the three cases of air flow velocity considered in this study. In case 1, in which the airflow velocity is the lowest (0.11 m/s), one may observe that several patches of airborne particles appear to have penetrated into the ultra-clean area, at the edges of the operating table where the surgical staffs are standing. A similar situation is also seen for case 2 in which the air flow velocity is slightly higher (0.18 m/s). However, for case 3 in which the airflow velocity is the highest (0.35 m/s), the airborne particles do not penetrate the ultra-clean area anymore. This observation suggests that higher air flow velocity from the LAF diffuser above the operating table is more effective in “washing” away the airborne particles from the vicinity of the ultra-clean area. This finding agrees well with the results reported by Chow et al. [9]. He stated that the air flow washing effect is ineffective at low air flow velocity. It usually causes the concentration air contaminants to exceed the recommended safe limit.

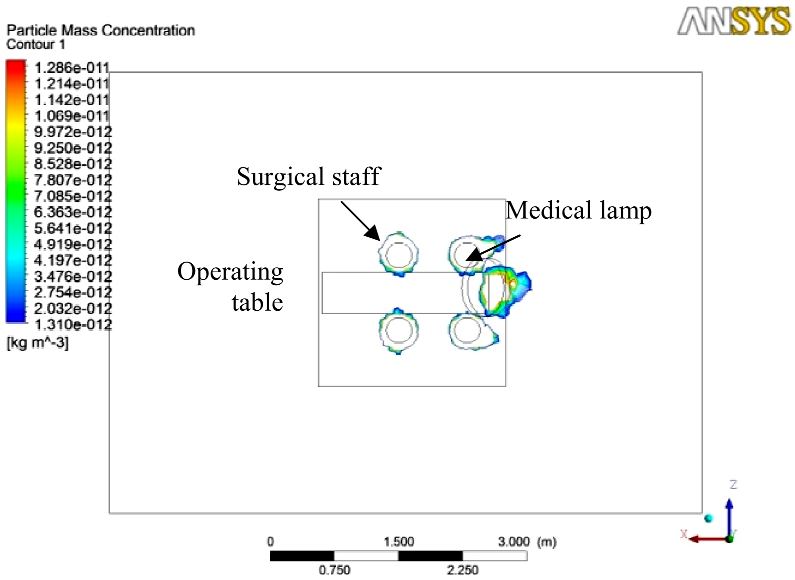


Figure 9 Particle mass concentration for *Case 1* (V_{inlet}=0.11 m/s).

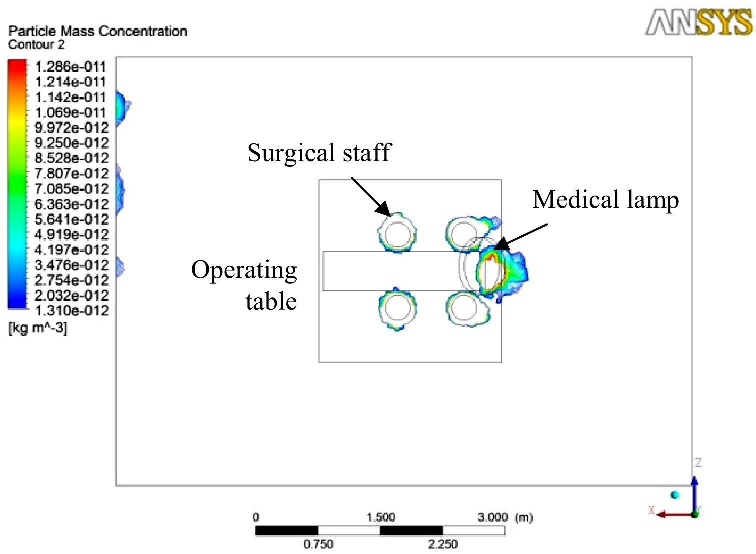


Figure 10 Particle mass concentration for *Case 2* (V_{inlet}=0.18 m/s).

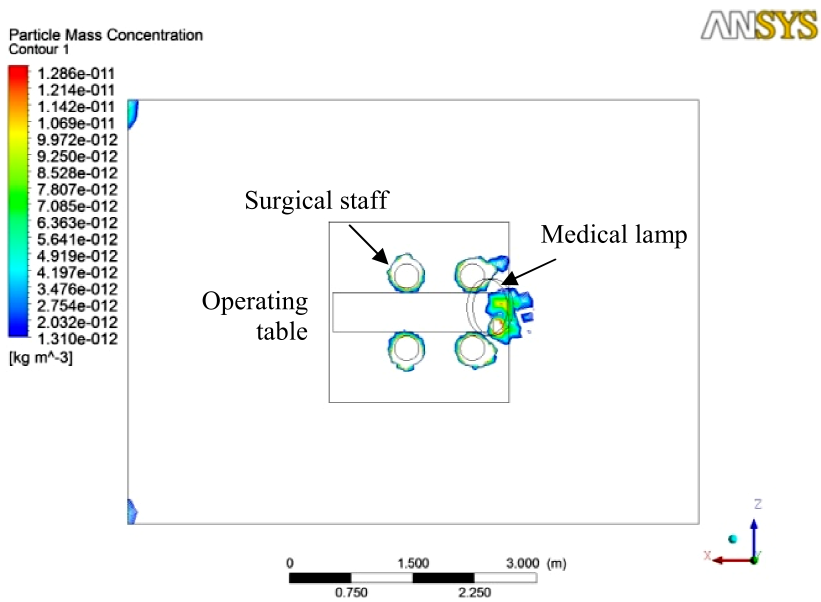


Figure 11 Particle mass concentration for *Case 3* (V_{inlet}=0.35 m/s).

One can also observe from Figure 9 through Figure 11 that there are much higher concentrations of airborne particles in the area beneath the surgical lamp. As described earlier, the presence of the lamp causes a disturbance on the laminar airflow from the LAF supply diffuser. A slightly lower pressure region was probably created below the lamp which causes a vortex air flow condition in this area. As a result, the surrounding air flows into this area, bringing along some airborne particles which then accumulated in this area. The simulation results also show that higher air flow velocity from the LAF supply diffuser increases the level of airborne particles concentration in this area. In a typical operating theatre, the medical lamp is located above the head section of the operating table. Thus, if the patient is undergoing surgery on his or her upper body section, the chances of him or her being infected during the surgical procedure could be higher.

Conclusion

This study was carried out to develop a validated CFD simulation model to be used to perform simulations to predict a steady-state airflow pattern and airborne particles trajectory paths inside a hospital operating theatre. Results of CFD simulation show that the air flows straight downward from the air-conditioning diffuser towards the middle of the operating table. However, the existence of the medical lamp causes a vortex air flow condition below it. Air also penetrates the ultra-clean area on the opposite side of the operating table. The airborne particles are washed away from the vicinity of the operating table by the air flow. This is more effective when the supply air flow velocity is high. At low air flow velocity, some particles appear to penetrate into the ultra-clean area at the edges of the operating table. At higher air flow velocity, the airborne particles seem to be more effectively washed away from this region. High concentration of airborne particles occurs underneath the medical lamp due to vortices created by the air flow. Higher air flow velocity increases the level of particles concentration in this area.

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