

Numerical Study of Airborne Particle Transport in an Operating Room

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Abstract

CFD (Computational Fluid Dynamics) modelling of particle transport has been applied for the control of airborne particles in the operating zone above the surgery table in an operating room. Based on the numerical results, it has been found that the particle source location, air (supply) inlet design, operating table location, and lamp design are among the critical parameters responsible for the particle distribution within the operating room.

Key words: operating room, air flow, particle distribution, particle concentration, numerical modelling

1. Introduction

The air quality in an operating room is one of the key components for reducing the postoperative infection rates of surgical procedures. It has been reported that 80%–90% of bacterial contamination found in an open wound comes from the ambient air. Cleaner air in the operating field results in a lower risk of sepsis (Nelson 1977, Lidwell et al 1982, and Hugh 1987).

To prevent infections after surgical operations, airborne particles in the operating room need to be controlled below a certain limit. Airborne particle transport in an operating room depends on many factors such as room geometry, inlet and outlet design, air displacement rate, number of persons in the room, particle source, equipment distribution, etc. Research shows that an aero-microbiologically clean zone should have less than 1 cfu/m³ (*colony-forming units*) (Hugh 1987) during an operation. To achieve this goal, the most straightforward way is to measure the particle concentration and to design an improved aero-microbiologically clean operating room. However, the experimental approach is not only expensive but many flow features and details are inaccessible to the instruments. Also the instruments and the person who conducts the experiment will disturb the flow field.

Since the emergence of digital computer systems, computational fluid dynamics, CFD, has been developed into a useful tool for the modelling of air flow, heat transfer, and particle transport. Already in 1992, Chen (1992) successfully conducted the numerical simulation of air flow and particle concentration in an operating room. He suggests that a higher inflow rate and larger inlet area will be helpful. Hartung and Kugler (1999) conducted a two-dimensional numerical modelling of an operating room. They suggest that the operating team and lamps can affect the air flow. However, as will be shown below, two-dimensional modelling is inadequate for any kind of realistic representation of the flow field and particle transport (Moser 2002).

This research is based on a test conducted in an operating room at Zurich University Hospital in Switzerland. The goal is to find the optimum design from a series of available choices, such as design of air supply canopy, air exit location, operating table arrangement, as well as the disturbance of the flow field by different lamps.

2. Physical Problem and Mathematical Model.

The objective of this research is to provide references for designing the ventilation system of the operating room in a hospital in Switzerland, as

shown in Figure 1a. The results of this study have been applied to the engineering design of the operating rooms by Meierhans AG and ADMECO AG in Switzerland. In this problem, the particle concentration distribution in the operating zone is the main concern. It is well known that bacteria (mostly at a size of 1 - 5 μm) are attached to particles. According to K ulpmann, (2002), the size of particles in a normal operating room is between 0.5 and 10 μm .



Figure 1a. An operating room at Zurich University Hospital shows heated person simulators that represent the surgeons.

The efficiency of particle displacement can be calculated as follows (K ulpmann, 2002):

$$\eta = (\log(\Phi_{ex}) - \log(\Phi_p)) / (\log(\Phi_{ex}) - \log(\Phi_{in})) \quad (1)$$

Where η is the efficiency of particle displacement, Φ_{ex} , Φ_{in} and Φ_p are the particle concentrations at the air exit, inlet, and the monitor point in the operating zone, respectively. Variable η is dimensionless, the dimension of Φ_{ex} , Φ_{in} and Φ_p is the particle number per cubic metre.

In this study, two monitoring points are defined to represent the air quality in the operating zone: one is situated 5 cm above the table centre, the other at the edge of the table near the head of the patient. If the air in the operating zone is as clean as the supply air, η is unity, if the particle concentration in the operating zone is higher than that of the supply air, but lower than that at the exit, η is between 0 and 1. So, η is taken as the criterion for comparing different cases.

For all cases involved, the particle source is placed below the main operating table. The particle concentration from the air supply is controlled at 100 particles per cubic metre, according to the experiment. The particle concentration in the operating region should not be higher than this value, while the particle concentration in the other region of the room may be as high as 10^7 particles per cubic metre.

The numerical method used here is based on the three-dimensional Reynolds-averaged Navier-Stokes equations closed by the shear stress transport (SST) turbulence model (Menter 1994). The space discretization is made by the finite-volume method. The commercial code CFX5.5 of AEA-CFX is used for the computations.

The continuity equation, momentum equation, thermal energy equation, and particle transport equation are solved simultaneously during the iteration process. The buoyancy effects are included according to the Boussinesq assumption (Kenjeres et al 2000). The surface temperature of the lamp, surgeons, and tables are fixed according to the field experiment. All the other walls are assumed to be adiabatic because they are well insulated. No-slip boundary conditions are imposed on solid surfaces. On the adiabatic walls, the heat received by radiation from other surfaces is released to the room air by convection. For the flow near the boundary layers, the scalable wall functions are employed (Grotjans et al 1998).

For this three-dimensional physical problem, we employed a non-uniform mesh layout. Fine mesh is applied where the velocity gradient is high or where the particle transport is of interest, such as the region below the curtain edge, near the persons' surface and the tables, etc. The total number of control volumes is about 300,000 cells, as illustrated in Figure 1b.

The particle transport balance is calculated as follows:

$$\psi = \frac{\sum_{k=i} V_{out,i} \Phi_{out,i}}{V_{in} \Phi_{in} + G_{particle}} \times 100\% \quad (2)$$

where $V_{out,i}$, V_{in} are the outlet volume flows and inlet volume flow, respectively; $G_{particle}$ is the particle generating rate, i.e., the generated particle number per cubic metre.

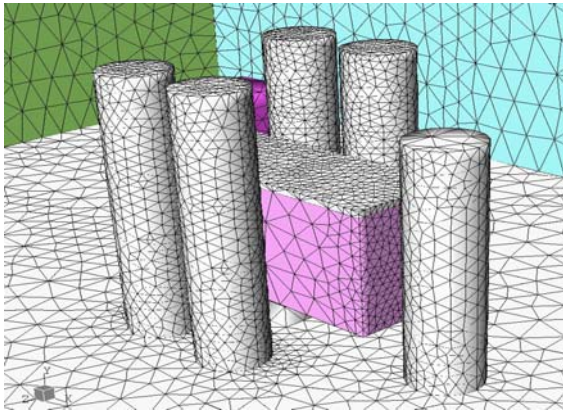


Figure 1b. Grid layout of an operating room.

The case runs are regarded as converged and are terminated after RMS residuals of all equations fall below 10^{-5} and the particle transport balance, ψ , is above 99%. For a typical run, about 20 hours CPU time is required on a 250MHz Silicon-Graphics Workstation, which has a memory of 1280MB.

3 Case Setup

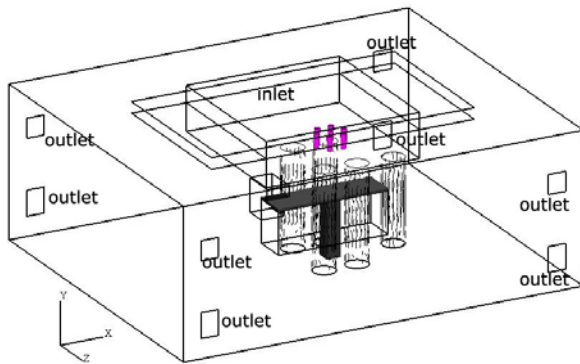


Figure 1c. General layout of an operating room.

As shown in Figure 1c, the operating room is 7.3 m long, 6.2 m wide, and 2.7 m high, all walls are well insulated, the supply of clean air is arranged to come into the room from the ceiling. A standard operating room layout is modelled by: A table, aligned with the edge of the inlet, and an instrument table situated below the laminar flow inlet, and five person simulators representing one surgeon and four assistant surgeons or nurses around the table, as shown in Figure 1a. To simplify the problem, all the medical personnel are assumed to be standing at rest, and a fixed temperature is imposed on the table surface to simulate the patient and the heating effect of the focused lights. To study the variation of

different cases, a standard case and four other cases are set up for comparison. In the standard case, the 6-lamp light (Figure 1d) is placed 0.6m above the table centre, and 0.75m below the air (supply) inlet. The exhausts are placed on the sidewalls. The particles are generated from below the main operating table at a rate of 1.20×10^8 per second. It is assumed that the particles follow the flow path without deviating from the streamlines of the air flow. The supply air flow is 8,000 m³ per hour, which corresponds to an air change rate of 67 ach. The supply air speed is 0.28345 m/s from the 2.8x2.8 m² inlet, where a 0.5 m high curtain, suggested by Meierhans AG (Meierhans 1999 and 2002 and K lpmann et al 2001) and is designed to maintain low-turbulence parallel flow.



Figure 1d. Picture of 6-lamp light.

Table 1 presents a list of the cases considered in this study. The standard case is from a real situation except that the persons around the table are represented by the person simulators. The 6-lamp light and the big light are all placed in the same position, the big light is a dish-shaped light with a diameter of about 0.9m, the 6-lamp light is made up of six 0.08m-diameter small lamps.

Table 1. Details of the cases.

#	Light type	Bed position	Air supply
A	6-lamp	at edge	8000 (m ³ /hr)
B	big	"	"
C	6-lamp	center	"
D	no light	at edge	"
E	"	"	4000 (m ³ /hr)

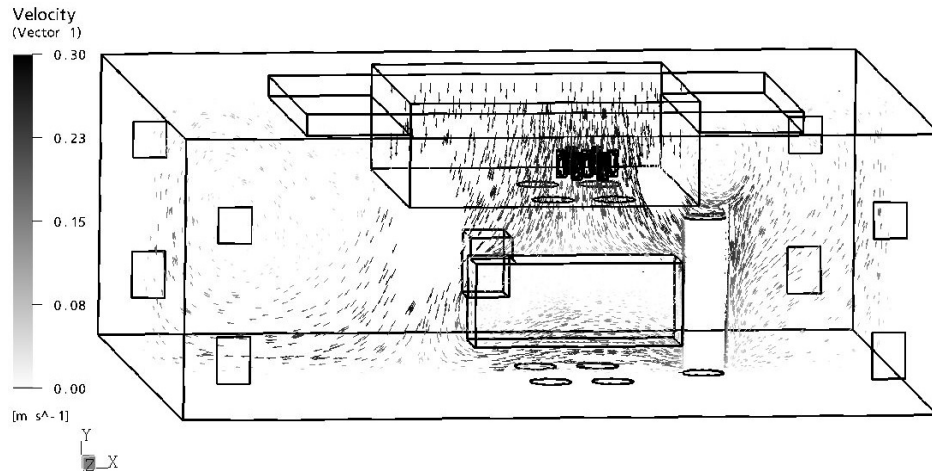


Figure 2a. Flow pattern in the centre plane of case A.

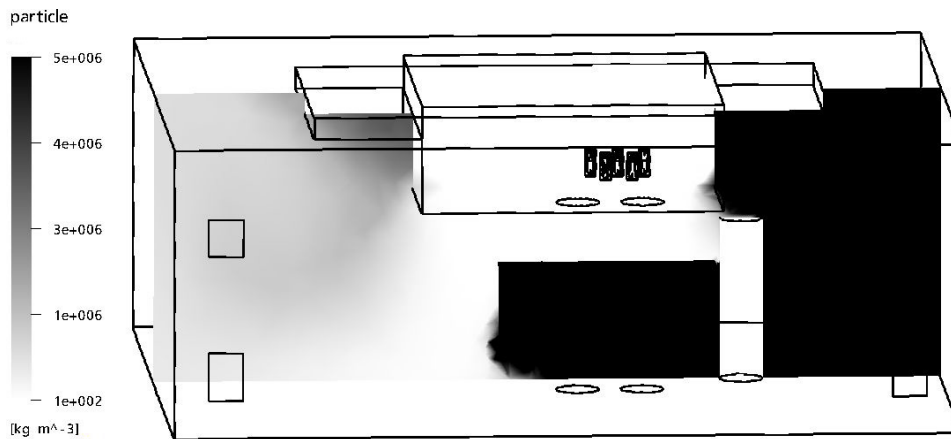


Figure 2b. Particle concentration in the centre plane of case A.

4. Results and Discussion

Figure 2a shows the streamlines of the air flow in the operating room for the standard case (case A). It shows that the fresh clean air coming from the laminar inlet, will spread in the whole room. After hitting the operating table, more air is pushed to the left side where it forms a recirculation pattern. This causes the air to flow from the left to the right below the main operating table, resulting in all particles generated under the table ending up on the right side, as shown in Figure 2b. The one-directional flow below the table is caused by the table location, – the right edge (head end of table) is aligned with

the edge of the curtain and not centred below the laminar flow inlet.

According to the computation for the laminar air supply of 0.28 m/s, no buoyant plumes are found above the 6-lamp light or large dish-shaped light. However, the large lamp will disturb the flow field so seriously that the particle concentration above the table is seriously affected. The particle displacement efficiency is only 14.9%, as shown in Table 2. Figure 3 shows the air flow vectors in the centre plane of the table (case B). It is obvious that it is not suitable for the large lamp to be positioned between the air (supply) inlet and the operating table.

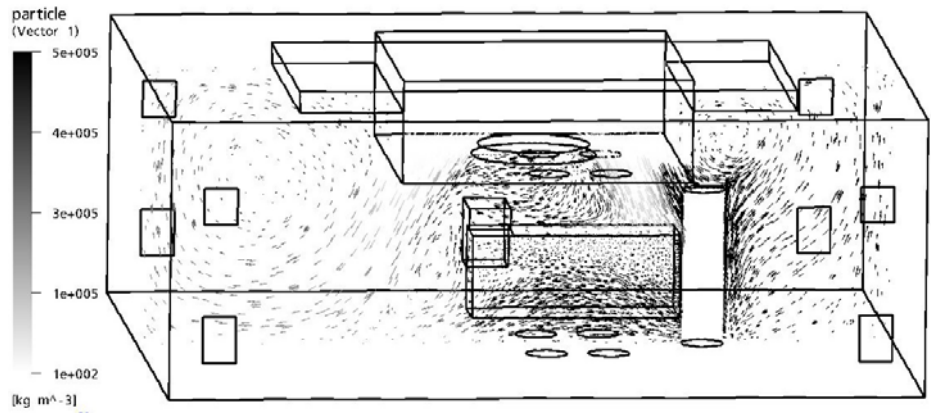


Figure 3. Flow pattern in the centre plane of case B.

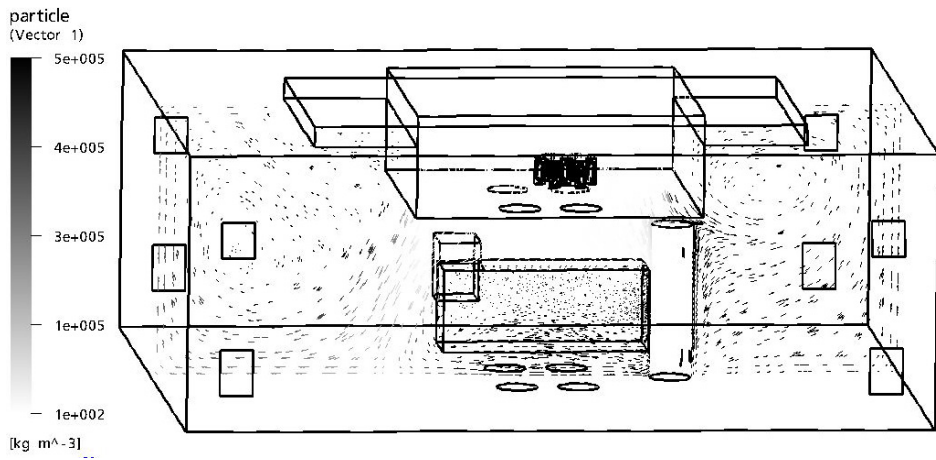


Figure 4. Flow pattern in the centre plane of case C.

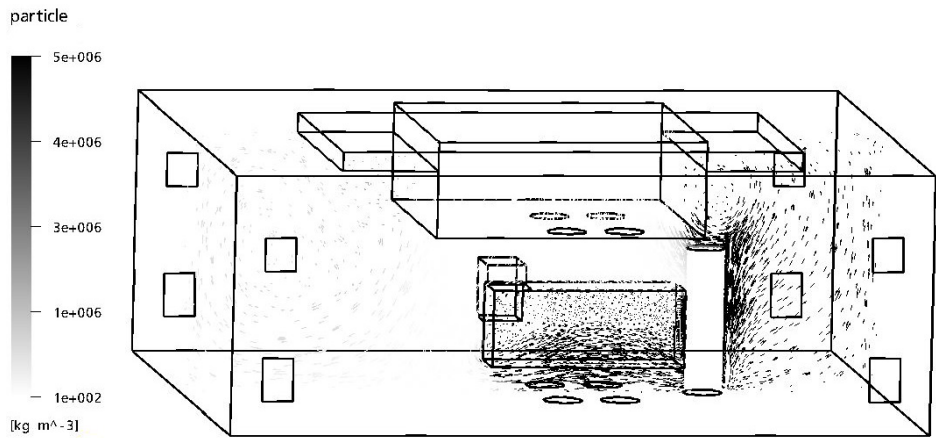


Figure 5. Flow pattern in the centre plane of case D.

Figure 4 shows the pattern with the table placed in the centre below the laminar flow supply (case C). Particles from below the table rise from either side of the table but do not reach the top of the table, and the air flow pattern is almost symmetrical. As the particle concentration on the left and the right of the table is much lower than in case A, it is a better design when compared with case A.

Figure 5 shows the pattern without lamps (case D). Because there are no disturbances for the inlet air flow, the air flow distribution is more uniform compared to case A. The particle concentration is

similar to that of case A, in which the flow pattern is not seriously disturbed by the 6-lamp light.

Compared to case A, if the inlet air flow is reduced from 0.28 m/s to 0.20 m/s, the momentum of the supply jet still dominates buoyancy effects. If the air speed is further reduced to 0.14 m/s, the thermal driving forces take effect and the upward buoyancy flow becomes apparent. This results in much higher particle concentrations above the table (case E), as shown in Figure 6. Its particle displacement efficiency is as low as 8.5%.

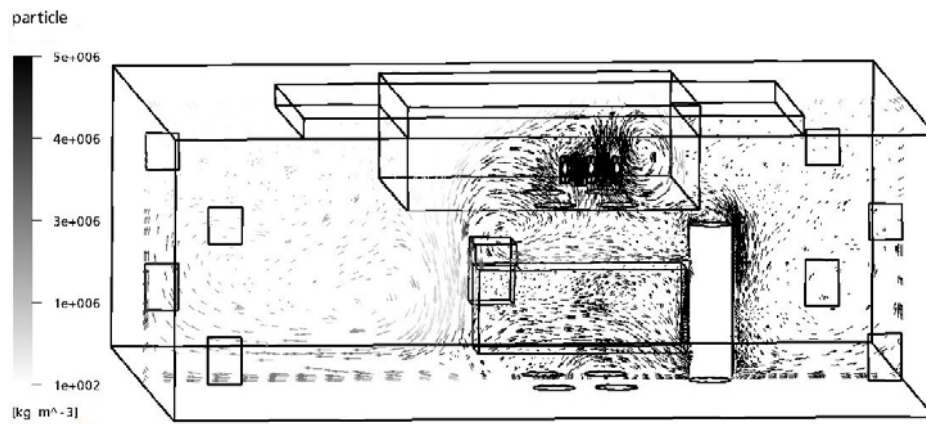


Figure 6a. Flow pattern in the centre plane of case E.

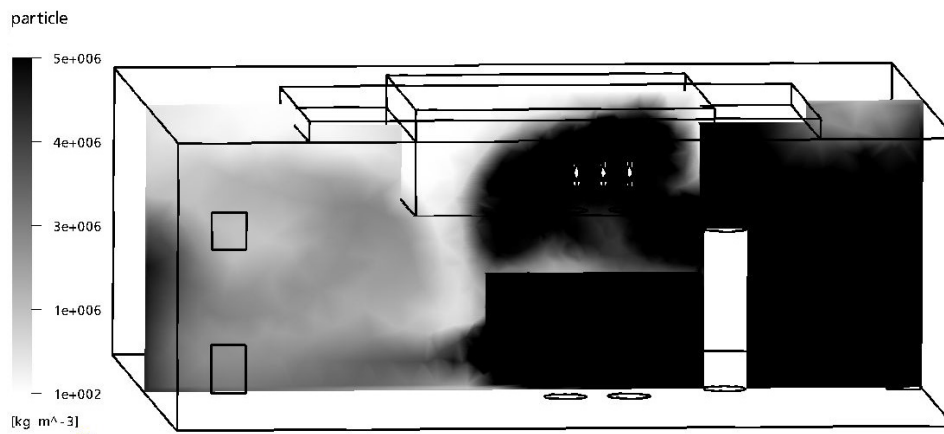


Figure 6b. Particle concentration in the centre plane of case E.

To compare the ventilation efficiency quantitatively, the particle displacement efficiency of all the above-mentioned cases has been calculated and listed in Table 2 and Table 3.

Table 2 shows that the low air supply velocity case and big operating lamp case give very poor particle displacement efficiency, so the design is not acceptable. The no lamp or 6-lamp configuration designed by ADMECO are much better.

Table 3 shows the particle displacement efficiency at the edge near the head of the patient. It shows that case A, case B and case E have a high particle concentration above the table edge.

Because the whole region above the operation table is of concern for maintaining a clean environment, it can be concluded that case C and case D give the best particle displacement efficiency.

Table 2. Comparison of the efficiency of particle displacement above the centre of the table.

#	Light type	Φ_p	Φ_{ex}	η
A	6-lamp	1×10^2	5.42×10^7	100%
B	big	7.6×10^6	5.42×10^7	14.9%
C	6-lamp	1×10^2	5.42×10^7	100%
D	no light	1×10^2	5.42×10^7	100%
E	6-lamp	1.2×10^7	1.08×10^8	15.8%

Table 3. Comparison of the efficiency of particle displacement above the table edge near the head of the patient

#	Light type	Φ_p	Φ_{ex}	η
A	6-lamp	4.4×10^5	5.42×10^7	36.5%
B	big	2.6×10^6	5.42×10^7	23.0%
C	6-lamp	1×10^2	5.42×10^7	100%
D	no light	1×10^2	5.42×10^7	100%
E	6-lamp	6.5×10^7	1.08×10^8	3.6%

5. Conclusions

It is generally known that the location of a particle source has a great influence on particle distribution. Minimising the particle source and the particle generation intensity will be helpful for maintaining a hygienically clean environment.

In addition to this, as discussed in this paper, for controlling particles in an operating room to achieve the designed level of cleanliness, especially above the operating table, the following should be considered:

1. Lights above the operating table will affect the air flow. In particular, the large dish-shaped lamp will cause recirculation above the table. This induces a higher particle concentration in the operating zone.
2. The table arrangement is very critical for particle transport in the operating room. If the table is not placed in the centre under the laminar flow inlet, asymmetric flow develops and all the particles generated from the doctors' feet will be pushed to one side of the operating room.
3. No buoyant plumes are detected above the lamp for an inlet air speed of 0.28 m/s. Buoyancy driven flow does exist above the lamps if the inlet air speed is reduced to 0.14 m/s.

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