# Numerical Investigation and Performance Evaluation of Laminar Ventilation Systems for Operating Room

Sanjeev Thool and Shobha Lata Sinha



December 10, 2019

# Numerical Investigation and Performance Evaluation of Laminar Ventilation Systems for Operating Room

S B Thool, Assistant Professor
Department of Mechanical Engineering
Dwarkadas J Sanghvi College of Engineering, Mumbai
S L Sinha, Professor
Department of Mechanical Engineering
National Institute of Technology, Raipur

**ABSTRACT**

Many emerging trends in the healthcare facilities such as evolution of treatment resistant bacteria and immune compromised patients is continuously contributing to post operative surgical site infection (SSI) in Hospitals. To control this, the only effective option left with us to maintain the infectious particle free environment in the operating room. This can be achieved by using effective ventilation system. Vertical Laminar airflow ventilation system is proved to be the most effective among others to achieve the same.

In this paper three configurations of laminar airflow ventilation systems have been evaluated in the view of controlling SSI using Computational Fluid Dynamics.

Results show that the laminar ventilation system having inlet air diffuser array covering entire ceiling area (Case-1) exhibits excellent performance but it is not feasible as the sizing of the laminar flow array. Laminar ventilation system with limited area of diffuse array located over the critical area and exhausts are located at bottom of both the walls opposite to each other (Case-2) exhibits performance near to performance of Case-1.

**Keywords:** Surgical Site Infection (SSI), CFD, Operating room, Surgical site, Back table, Air distribution.

## 1. Introduction

Despite continuing advances in medical science surgical site infections (SSI) remain a substantial cause of morbidity and mortality among hospitalized patients. There are many emerging trends in the healthcare environment, which are contributing to this. One such trend is the evolution of treatment resistant bacteria. The most common cause of SSI is a pathogen called Staphylococcus aureus accounting for approximately 20% of cases in a study done by Kirklant [1]. Staphylococcus aureas is commonly found on normal human skin [2]. The transmission of Staphylococcus aureas is especially troubling due to the fact that in recent years, several strands of the bacteria have been found that are resistant to traditional antibiotics [2]. It is important to note that as various pathogens develop resistance to standard treatment, some much faster than Staphylococcus aureus, the doses and types of medication get stronger. However as this occurs the resulting side effects, treatment time and costs also increase.

Another emerging trend in healthcare is the increased numbers of immune compromised patients and immune suppressing treatments. This includes an increased number of patients who are elderly and / or have a wide variety of chronic, weakening or immune compromising core diseases. There are also increased numbers of prosthetic implant; bone marrow transplant and organ transplant operations performed where the immune system is intentionally suppressed.

The major source of microbiological particles in the operating room is from the surgical staff and is proportional to the number of people moving about in the room. Therefore the goal of any system has to be the isolation of the patient from the microbiological particles produced by the surgical team and the support staff in the operating room. It is indented to maintain proper air flow pattern so that contaminant will safely be removed from the operating room through the exhaust without get struck on the significant items of equipment.

The best way to treat an infection is to stop it from occurring in the first place. The modern hospital environment is changing rapidly. Due to this fact, selection of the proper air distribution system for the modern operating room is very difficult process. Over the past 50 years there have been many attempts to justify particular systems. But it is a common consensus that the flow pattern of clean or ultra clean air is very important for infection control in operating room.

Now a days, downward unidirectional (laminar) flow is widely adopted air distribution for creating an aseptic environment around patient. In this study, Computational Fluid Dynamics (CFD) is used as tool to predict the air distribution and particle dispersion for the various configurations of the vertical laminar airflow ventilation system.

## 2. CFD Modeling

### 2.1 The turbulent airflow model

The present study has been carried out using Eulerian method to simulate the airflow field. The interaction between fluid phase and discrete phase is assumed to be one way, and the impact from discrete phase to fluid phase is negligible. This is feasible since the particle volume fraction is sufficiently small. Thus the airflow field is independent on the particulate phase and could be determined in advance.

The following generic equation present the three-dimensional form of the governing equations for the conservation of mass, momentum, energy, and turbulent quantities. Here general variable ϕ is introduced and express all the fluid flow equations of temperature and turbulent quantities, in the conservative incompressible form.

$$\frac{\partial(\rho\phi)}{\partial t}+\frac{\partial(\rho V\phi)}{\partial x}+\frac{\partial(\rho V\phi)}{\partial y}+\frac{\partial(\rho V\phi)}{\partial z}=\frac{\partial}{\partial x}\left[\mathcal{T}_\phi\frac{\partial}{\partial x}\right]+\frac{\partial}{\partial y}\left[\mathcal{T}_\phi\frac{\partial}{\partial y}\right]+\frac{\partial}{\partial z}\left[\mathcal{T}_\phi\frac{\partial}{\partial z}\right]+S_\phi \quad \text{....(1)}$$

By setting the transport property $\phi$ equal to 1, $u$, $v$, $w$, $T$, $k$, $\varepsilon$, selecting appropriate values for the diffusion coefficient $\mathcal{T}_\phi$ and source term $S_\phi$, we obtain the special forms presented in table 1 for each of the partial differential equations for the conservation of mass, momentum, energy and the turbulent quantities.

**Table 1: General form of governing equations for incompressible flow in Cartesian coordinates**

| Equations | $\phi$ | $\Gamma_\phi$ | $S_\phi$ |
|---|---|---|---|
| Continuity | *1* | *0* | 0 |
| u-momentum | $u$ | $\nu + \nu_T$ | $-\frac{1}{\rho}\frac{\partial p}{\partial x} + S'_u$ |
| v-momentum | $v$ | $\nu + \nu_T$ | $-\frac{1}{\rho}\frac{\partial p}{\partial y} + S'_v$ |
| w-momentum | $w$ | $\nu + \nu_T$ | $-\frac{1}{\rho}\frac{\partial p}{\partial z} + S'_w$ |
| Temperature | $T$ | $\frac{\nu}{Pr} + \frac{\nu_T}{Pr_T}$ | $S_T$ |
| Turbulent kinetic energy | $k$ | $\frac{\nu_T}{\sigma_k}$ | $P - D$ |
| Energy dissipation rate | ε | $\frac{\nu_T}{\sigma_\varepsilon}$ | $\frac{\varepsilon}{k}(C_{\varepsilon 1}P - C_{\varepsilon 2}D)$ |

where

$$P = 2\nu_T\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \nu_T\left[\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)^2\right]$$

and $D = \varepsilon$

## 2.2 Equations for Particle Motion and Dynamics

The Lagrangian particle tracking method has been used to calculate individual trajectories by solving the momentum equation. Particles motion in carrier fluid is affected by various forces such as viscous drag force, gravity force, added mass force (virtual mass force), Brownian force, and pressure force. In this study, Brownian force has been ignored due to the large size of particle. The added mass force is considered in a few simulations and is found to have negligible influence on particle trajectory. Thus in this study, steady viscous drag force, gravity force and pressure force have been considered. Therefore the final form of the trajectory equation become

$$m_p\frac{du_p}{dt} = \frac{1}{2}C_D A_p \rho(u - u_p)\sqrt{(u - u_p)^2 + (v - v_p)^2 + (w - w_p)^2} + m_p g_x \quad \text{....(2)}$$

$$m_p\frac{dv_p}{dt} = \frac{1}{2}C_D A_p \rho(v - v_p)\sqrt{(u - u_p)^2 + (v - v_p)^2 + (w - w_p)^2} + m_p g_y \quad \text{....(3)}$$

$$m_p \frac{dw_p}{dt} = \frac{1}{2} C_D A_p \rho (w - w_p) \sqrt{(u - u_p)^2 + (v - v_p)^2 + (w - w_p)^2} + m_p g_z \quad ....(4)$$

where, $C_D = \frac{24}{Re_p}$ ……… for $Re_p$ <1;

$C_D = \frac{24}{Re_p}(1 + 0.15 Re_p^{0.687})$ ……… for $1 \leq Re_p < 400$;

## 3. Outline of Baseline Model of Operating Room

A typical operating room layout is consists of the number of five surgical staff members, lights, machinery, tables and patient is considered for the baseline model for the CFD simulations. The features of the baseline room are given in Table 2.

**Table 2**
**Dimension and Heat Dissipation of Major Items in Operating Room**

| Item | Dimensions | Heat Dissipation | Heat Flux |
|---|---|---|---|
| Operating table | 0.64 m x 2.0 m x 0.9 m | None | -- |
| Surgical lamp | 0.55 m x 0.55 m x 0.1 m | 150 W | 182 W/m$^2$ |
| Anesthesia machine | 0.6 m x 0.6 m x 1.1 m | 200 W | 76 W/m$^2$ |
| Back table | 0.64 m x 1.6 m x 0.9 m | None | -- |
| Monitor stand | 0.6 m x 0.5 m x 1.20 m | None | -- |
| Monitor | 0.5 m x 0.4 m x 0.6 m | 200 W | 185 W/m$^2$ |
| Surgical staff (Two surgeon and three nurses) | 0.46 m x 0.28 m x 1.8 m each | 100 W each | 37 W/m$^2$ each |
| Patient | 0.46 m x 0.28 m x 1.8 m | Exposed head dissipates 46 W. Surgery site (0.3 m x 0.3 m) area with surface temperature = 38 ˚C | -- |

## 4. Model Considerations

In this section, only the cases of vertical laminar airflow ventilation systems with different configurations have been considered for numerical simulation along with comparison amongst them. In Case-1, arrays of supply grills fill entire ceiling where as in Case-2 and Case-3 array of supply grills of size 1.83 m x 2.44 m is fixed immediately above the operating table. The different ventilation systems considered, which are listed in table 2 are replicated approximately those outlined in Memarzadeh and Manning. For this study, the particles (skin flakes) are assumed to have the density of the oil smoke particle, i.e. $\rho_P = 850$ kg/m$^3$ and diameter of 15 micron.

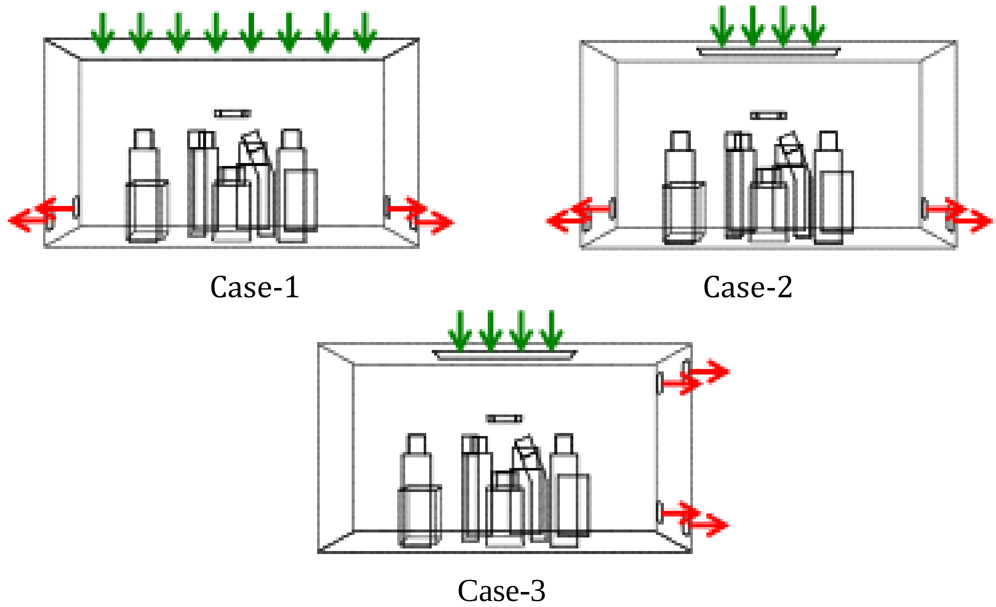


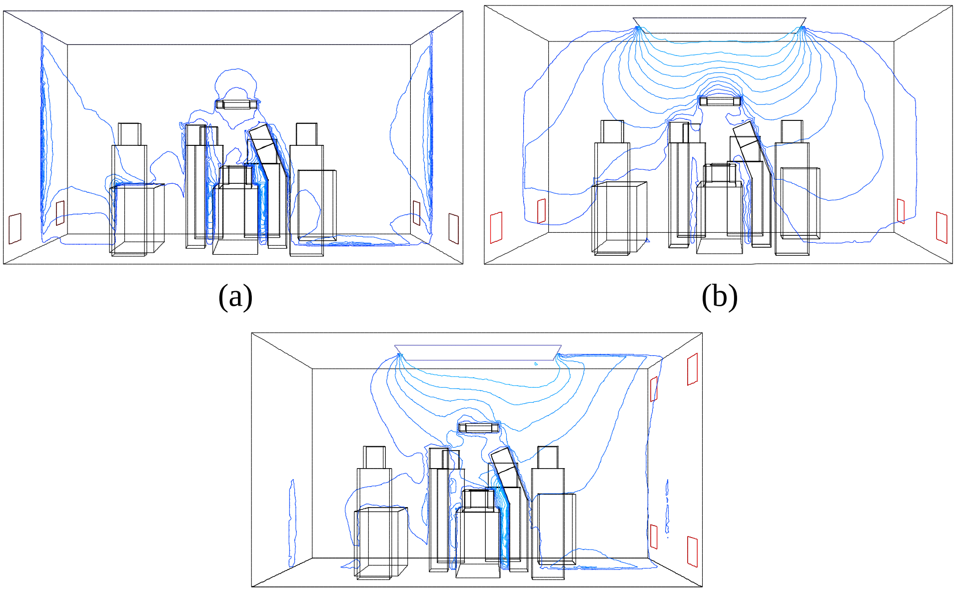

**Figure 1** Various configuration of Vertical Laminar Airflow Ventilation System

**Table 2** Brief of different Ventilation Systems

| **Case** | **System** | **Diffuser Details** | **Volume flow rate in m$^3$/s** | **ACH** | **Supply velocity in m/s** | **Brief** | **Diffuser Type in Cases** |
|---|---|---|---|---|---|---|---|
| 1 | Laminar | Entire ceiling has laminar flow supply (6 m x 4.2 m) Exhaust are 0.36 x 4.2 m | 3.36 | 150 | 0.13 | Exhaust grilles are located at low level (two sides) | Laminar supply |
| 2 | Laminar (both side low level exhaust) | Array of supply grilles immediately above table (1.83 m x 2.44 m) | 0.47 | 27.45 | 0.14 | Exhaust grilles are located on both side at low level | Laminar (supply) Conventional (exhaust) |
| 3 | Laminar (mixed level exhaust) | Array of supply grilles immediately above table (1.83 m x 2.44 m) | 0.47 | 27.45 | 0.14 | Exhaust grilles are located on one side at high and low level | Laminar (supply) Conventional (exhaust) |

## 5. Results of Numerical Simulation

FLUENT software is used for numerical simulation of all cases (Fig. 1.a). For Case-1, numerical simulation is carried out for ACH of 150 $h^{-1}$, which is within the range of value of ACH as stated by Memorzadeh and Manning. It clearly shows that the air motion set up by the physics of the space nearly guarantees the induction of contaminated particles into the flow. This is because of recirculating air resulting from the need for room pressurization, which requires roughly 10% less air leaving the space than being supplied to it. Functionally, if less air is leaving the space than entering it, some air in the space must recirculate. By definition, recirculating air is aging air and, therefore, is gathering particles. These particles, being immediately adjacent to the accelerated airflow, can be induced into it. And because of the coalescence, this particle induced could take place within the sterile zone. Again as to fill entire ceiling area by laminar arrays, it requires increased cold air mass, more potential energy, and more of the flow to accelerate after leaving the diffuser.



(a) (b)

(c)

**Figure 2** Velocity Contours (at vertical plane at z = 0) for (a) Case-1, (b) Case-2, (c) Case-3

In Case-2, exhausts are located at bottom of both the walls opposite to each other. In simulation result (Fig. 1.b), it has been found that velocity distribution covers the whole area around the critical area covering all surgical staff and equipment. Velocity of air (0.11 m/s) at area above the surgical site is relatively very low as compared to other cases. Again two recirculation zones on both the sides of the patient are very weak as compared to other cases. Since the air velocity above the surgical site is very low, thermal plume generated by the surgical site becomes effective which drives the particles up to the high level exhaust and obstruct the particles from settling down on the critical area.

In Case-3, air is exhausted at low and high level from only one wall. In simulation results (Fig. 1.c), it has been found that effective velocity distribution covers only half part of the room towards the exhaust wall, leaving relatively stagnant region in opposite part of the room. It causes the particles that trapped in this stagnant region will not be exhausted and fall on surface of back table. It has also been found that the recirculation region is created between the main surgeon and patient. This will cause the particles remain suspended in this area, which may cause to trap on surgical site. Lighter particles generated by the Surgeons and nearby Nurses are effectively exhausted through the top outlet by following the velocity pattern. But on back table side, particles generated by nearby Nurse and second Surgeon remain suspended and may settled down on back table surface.

## 6. Particle Trajectory Simulations and Performance Discussion

All the ventilation systems discussed above provide laminar flow regimes. These exhibits the comparable option for an operating room in terms of contamination control, as they result in the smallest percentage of particles impacting the surgical site. However Case-1 is not feasible as the sizing of the laminar flow array. A face velocity of around 0.13 to 0.16 m/s is sufficient for these types of ventilation systems depending on size of laminar diffuser array.

Table 3 shows the comparison of performance of the above mentioned ventilation systems on the basis of number of particles escaped from the room, number of particle strike on the Site of Surgery and number of particles strike on the surface of Back Table. All cases exhibits less than 1% of particles that hit the surgical site from the Surgeons and Nurses. This is because the relative dominance of the thermal plume caused by the surgical site (wound / body part under surgery). It is only when the particles are released close to the site, in particular, the source of main surgeon performing operation. Although the Case-1 exhibits comparable performance in terms of particles escape, it appears not feasible to fill entire ceiling with laminar grill panels.

Case-3 displays comparatively poor performance as compared to others in terms of percentage of particles escaped from the operating room and percentage of particles strike on surgical site and back table.

**Table 3**

Percentage of Particles Vented from Room and Percentage of Particles Strike on Surgical Site and Back Table for Case-1 to Case-5

| Cases | Particle Source | Total Number of particles released | Contaminated particles escaped from Operating Room | | Contaminated Particles Strike on Surgery Site | | Contaminated Particles Strike on Back Table | |
|---|---|---|---|---|---|---|---|---|
| | | | Nos. | % | Nos | % | Nos | % |
| Case-1 | Surgeons | 512*2 = 1024 | 945 | 93.2 | 1 | 0.10 | 1 | 0.10 |
| | Nurse | 512*3 = 1536 | 1519 | 98.9 | 0 | 0.00 | 0 | 0.00 |
| Case-2 | Surgeons | 564*2 = 1024 | 950 | 92.8 | 1 | 0.10 | 1 | 0.10 |
| | Nurse | 564*3 = 1536 | 1517 | 98.7 | 0 | 0.00 | 0 | 0.00 |
| Case-3 | Surgeons | 512*2 = 1024 | 891 | 87.1 | 1 | 0.10 | 1 | 0.10 |
| | Nurses | 512*3 = 1536 | 816 | 53.1 | 0 | 0.00 | 4 | 0.26 |

## 9. Conclusions

Observations from the simulation results reveal that Case-1 and Case-2 perform excellent in removal of particles via ventilation. It is not continued to decrease. Again it has been found that on comparing on the basis of ACH, it is not significant in the surgery source / surgery site analysis as design of the ventilation system. It is has also been demonstrated by all the system exhibiting less than 1 % of the particles that hit the surgical site from the Surgeons and Nurses. This is because the relative dominance of the thermal plume caused by the surgical site.

Systems that provide laminar flow regimes represents the best option for an operating room in terms of contamination control, as they results in the smallest percentage of particles impacting the surgical site. However, care needs to be taken in the sizing of the laminar flow array. A face velocity of around 0.13 to 0.18 m/s is sufficient from the laminar diffuser array, provided that the array size itself is set correctly.

Case-3 preforms comparatively weak as compared to Case-1 and Case-3 in terms of contaminated particles escaped from Operating Room and striking of particles on the back table, which are generated from the Nurse sources.

## NOMENCLATURES

| Symbol | Description |
|---|---|
| $C_D$ | drag coefficient |
| $dt$ | time interval |
| $G$ | Gravitational acceleration |
| $k$ | Turbulent kinetic energy |
| $T$ | Temperature |
| $t$ | Time |
| $Pr$ | Prandtl Number |
| $V$ | Velocity |
| $u, v, w$ | instantaneous velocity of air in x, y and z directions |
| $A_p$ | cross-sectional area of the particle |
| $m_p$ | mass of particle |

**Greek Symbols**

| | |
|---|---|
| $\varepsilon$ | Turbulent kinetic energy dissipation rate |
| $\alpha$ | Thermal diffusivity ($k/\rho c_p$) |
| $\mu$ | Dynamic Viscosity |
| $\rho$ | Mass density |
| $v$ | Kinematic viscosity ($\mu/\rho$) |
| $v_t$ | Turbulent kinematic viscosity |

**Superscripts**

| | |
|---|---|
| - | Time-averaged value |
| ’ | Fluctuating value |

**Subscripts**

| | |
|---|---|
| *x, y, z* | Abscissa and ordinate of rectangular Cartesian coordinate system |
| *p* | Particle |
| *T* | Turbulent flow |

## REFERENCES


[1] Kirkland, Kathryn, Jane Briggs, Sharon Trivette, William Wilkinson, Daniel Sexton, The Impact of Surgical-Site Infections in the 1990s: Attributable Mortality, Excess Length of Hospitalization, and Extra Costs, *Infection Control and Hospital Epidemiology*, Volume 20, No. 11, (1999).

[2] Todar, Kenneth. *Staphylococcus*. Updated: 2005. Accessed: 16 August, (2007). <http://www.textbookofbacteriology.net/staph.html>.

[3] Loomans, M., Lemaire, T., Particle concentration calculations using cfd - a comparison. *In: Proceedings of Indoor Air 2002*. Edinburgh, Scotland, pp. 153–156 (2002).

[4] Riddle, A., Carruthers, D., Sharpe, A., McHugh, C., Stocker, J., Comparisons between FLUENT and ADMS for atmospheric dispersion modeling. *Atmospheric Environment*, pp. 1029–1038 (2004).

[5] Launder, B.E., Spalding, D.B., Lectures in Mathematical Models of Turbulence. *Academic Press*, London, England (1972).

[6] FLUENT, 2005. Fluent 6.2 User's guide. Fluent Inc., Lebanon, NH.

[7] Patankar, S.V., Numerical Heat Transfer and Fluid Flow, *McGraw Hill*, Washington, (1980).

[8] Thool S.B. and Sinha, S.L., Simulation of room airflow using CFD and validation with experimental results, *International Journal of Engineering Science and Technology*, Vol. 56, No. 6, pp. 1526–1532 (2014).

[9] Sinha, S.L., Arora, R.C, and Subhransu Roy, Numerical Simulation of Two Dimensional Room Air Flow with and Without Buoyancy, *Energy And Buildings*, 32(1), pp. 121–129 (2000).

[10] Farhad Memarzadeh, Andrew P. Manning, Comparison of Operating Room Ventilation Systems in the Protection of the Surgical Site.

[11] W C Hinds, Aerosol Technology, Properties, Behavior, and Measurement of Airborne Particles. *Wiley*, New York, (1982).

[12] B Friber, Ultraclean laminar airflow in operating rooms, AORN Journal, April, 1982.

[13] W Whyt, O M Lidwell, E J L Lowbury, R Blowers, Suggested bacteriological standards for air in ultraclean operating room. J Hosp Infect 1983;4: pp. 133—139.