Contaminant Removal from Virtual Operation Room

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Abstract. Most bacterial contaminants found in operation rooms come from patient’s exhale or from wounds after surgery that make colony forming units. Thus, yearly, a lot people suffer from infections acquired during surgical procedures. Removing pollutants from operation room by investigating the influence of different locations and types of entry and exit grills is the subject of the present work. Equations of fluid flow including the continuity, momentum, energy equations and species equation have been numerically solved by using the FLUENT ANSYS v.14 for virtual symmetric operation room taken in this paper. Turbulent flow of mixture material species is applied in the model of operation room. Standard K-epsilon was used for simulating turbulent flow pattern. The present study aims to find a proper arrangement of inlet and exhaust locations to reduce the unfavorable factors in operation room such us, contamination, humidity, temperature and also air velocity. These factors were achieved according to modification in inlet and exhaust grills arrangement and then simulated through FLUENT software program. Six different arrangements of supply and exhaust were studied to determine case of best health and comfort demands. Case no 5, using local exhaust ventilation, shows good improvement in removing contaminants. However, case no 6 which uses both local exhaust ventilation and like air curtain air supply, shows the optimum removal of contaminants, because it shows lower contamination mass fraction. Meanwhile, the worst contaminant removal were in case 2 and case 1, where source of contaminant exists in low movement zone (dead zones) or region of separation of streamlines. The results showed, using both local exhaust ventilation and like air curtain air supply as in case (6) maintains an average temperature of 21.3 $^\circ$C, the least amount of particles mass fraction of contaminants 6.36E-08 and moisture content of 0.009.

Keywords. Computational fluid dynamics, Ventilation of operation room, Contaminants removal.

1. Introduction
There is a relation between effectiveness of ventilation systems and contamination of the surgical wound degree [1, 2]. The danger of infection is directly related to the indoor air quality (IAQ) of a surgical room [3]. Reducing bacteriological load level, in operation room, to minimum possible value is needed to prevent infections in surgical site [4,5], high-performance hospital operation rooms have the suitable HVAC system, usually unidirectional flow [6], to carry out complex surgeries because of high level of sepsis that may be found in the field of operation room. Designing parameters of HVAC installations in high-performance operating theatres were evaluated according to ASHRAE
Applications Handbook 2003 [7]. According to ASHRAE recommendations in an operating room, temperature should be kept in the range of (20–24°C), relative humidity should be kept between 50% and 60%, positive air pressure should be maintained, and all air exhaust with no recirculation is preferred. Sánchez-B (2019) [8] analyzed indoor environmental conditions and design requirements for heating, ventilation, and air-Conditioning (HVAC) systems in high-performance operation rooms. Attia (2013) [9] assured numerically that door opening affects thermal comfort badly. The air curtain was found to improve thermal comfort conditions. Three dimensional investigations of uni-directional flow in an operation room with side exhaust and ceiling supply grills is done. Temperature is used to judge the patient and staff members’ thermal comfort. Ho (2009) [10] studied contaminant removal and thermal comfort in an operation room, using CFD simulation to numerically solve equations of fluid flow, and heat and mass transfer inside the operation room. Thermal comfort of occupants was assessed by model of predicted mean vote (PMV). Nine models of CFD simulations were done to test influence of different possible arrangement of supply and exhaust grilles on contaminant removal and thermal comfort. Chang (2007) [11] investigated numerically ventilation pattern impact on contaminant transport behavior in two-room building using natural ventilation. Chow and Yang (2004, 2003) [12,13] simulated contaminant dispersion with both CFD and experimental case study and concluded that CFD simulation is a suitable tool for better understanding the ventilation design. Ho (2005) [14] simulated two typical working spaces to find effects of contaminant removal and thermal comfort on operation room when different configurations of outlet and inlet arrangements, and on an office with two cases of air distribution systems: under floor and overhead, also with alternative cases. The 2-D simulation approach was employed. Temperature, relative humidity, concentration of contaminant, predicted mean vote (PMV), and contaminant removal factor were computed and used for assessing thermal comfort and contaminant removal characteristics of the office room and operating room. The results show good agreements with data taken from related literature. Bahador (2017) [15] numerically studied the outlet airflow through a laminar flow diffuser in order to find the optimal airflow velocity to reduce the air contamination in the surgical site of operating rooms. The results show that an air curtain having an optimal velocity of the outlet air greatly influences the reduction of air contamination, maintaining the more desired conditions and a better flow pattern. ALFA, M. T (2019) [16] attempted to assess perceptions of patients of the indoor environment of divisions in a hospital according to thermal comfort, architectural design, indoor air quality (IAQ), lighting and acoustical parameters. The study tried to determine factors that influence perceived indoor environmental quality and explored the relation between perceived importance of indoor environmental quality and health recovery, health satisfaction and therapeutic ambience of the hospital. A field study of the indoor environmental quality of four wards in the General hospital at some places was collected, and responses from many patients were obtained. It was observed that the most significant parameter on perceived indoor environmental quality is health of patients. Keshtkar (2016) [17] focused on the simulation of a three-dimensional laminar flow air conditioning system with air curtain in the operating room and tried to find the optimum velocity of air curtain to conduce the lowest contaminants in surgical zone. Model of laminar air flow system with air curtain was designed considering the contamination factor caused by doctors, nurses, and patients, and also transmitted through the entrance of the operating room, in order to find and suggest the best area of the operation room (concerning contamination, velocity, air temperature, etc.), and compared the behavior of the system and its performance with and without air curtain. Loomansa (2018) [18] examined the influence of spatial transitions within workspaces, across different thermal conditions, on thermal acceptability of occupant. It was observed that when the air temperature differences were within ~ ±2°C, occupant thermal perception was not affected by the transition temperature difference. Khalil (2004) [19] Kameel and Khalil studied the relationship between air quality and thermal comfort in healthcare facilities to optimize air quality in buildings where intensive healthcare is needed. The objective of present paper is to select the best design of ventilation, by which better thermal comfort and minimizing contaminant diffusion in a regular operation room can be achieved. Simulation of different possible designs of ventilation is needed to select the best design. Three-dimensional full-scaled model of operation room was built to simulate problem numerically. The CFD model was validated by comparing with Son H. Ho [10] for the same model. Effects of variation in locations of
air supply grilles and exhaust grilles were examined according to their position in CFD models. The stream lines, temperature, relative humidity and contaminant concentration are found and examined to explore the related transport phenomena. CFD models for six different arrangements of the locations for two kinds of the supply and exhaust grilles were conducted to examine the influence induced by these types and locations on contaminant removal and thermal comfort.

2. Mathematical model
Fluid flow in any domain is governed by a combination of continuity equation, momentum equations and other related equations such as energy and pollutant transport equation. These equations are shown in table (1). Also, these basic laws can be written in terms of partial differential equations (PDE’s) for any flow in laminar or turbulent manner. In this study, simulation of air motion is assumed to be three dimensional, turbulent, incompressible and in steady state flow. The present study includes a familiar operation room with dimensions of (6.1 m x 4.3 m x 3.0 m). The basic arrangement of the operation room is shown in figure 1. Due to this symmetry, only a half of the room needs to be modeled as indicated in figure 1-b. Six cases for different arrangements of entry and return grill are shown in figure 2. The dimensions for six modeled room according to types of air supply diffuser and exhaust grill were also illustrated in table (2). The patient’s body was modeled as a rectangular box laid horizontally in the operation room with dimensions of (1.7 m x 0.3 m x 0.5 m) as shown in figure 1-d. The patient’s body surfaces are assumed to be at constant temperature and have constant fluxes of water vapor and contaminant. All staff members are modeled as rectangular boxes standing vertically with dimensions of (1.7 m x 0.3 m x 0.5 m) as shown in figure 1-c. Surfaces of staff member were assumed to be at constant temperature and have constant flux of water vapor but zero flux of contaminant. Rectangular box shape was used for modeling surgical light above the patient with dimensions of (0.7 m x 0.65 m x 0.3 m) as shown in figure 1-e. Bottom surface of surgical light is the major source of heat load supplied to occupied zone. Boundary conditions used to solve the numerical values are set according to the locations as described in table (3). Elements number inside operation room were increased gradually until reaching grid independency of 323594 elements with 340784 nodes as shown in figure (3). Only hexahedron type elements were used in mesh construction as shown in figure (4). All case studies were analyzed by FLUENT ANSYS v. 14. Solution was considered to be converged when residual error of continuity, velocity components and species reaches $10^{-3}$ and residual error of energy reaches $10^{-6}$.

![Figure 1. Model of operation room.](image_url)
Table 1. The basic laws of fluid flow field.

| No. | Name                                                      | Mathematical formula                                                                 |
|-----|-----------------------------------------------------------|--------------------------------------------------------------------------------------|
| 1   | The equation for the conservation of mass               | \( \frac{\partial}{\partial x} (\rho u) + \frac{\partial}{\partial y} (\rho v) + \frac{\partial}{\partial z} (\rho w) = 0 \) |
| 2   | Conservation of momentum (Navier–Stokes Equations)      |                                                                                      |
| 2-1 | x-direction (U-momentum)                                 | \( \frac{\partial}{\partial x} (\rho u) + \frac{\partial}{\partial y} (\rho v) + \frac{\partial}{\partial z} (\rho w) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + \frac{\partial}{\partial x} \left( \rho \frac{\partial u}{\partial x} \right) \) |
| 2-2 | y-direction (V-momentum)                                 | \( \frac{\partial}{\partial y} (\rho v) + \frac{\partial}{\partial z} (\rho w) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) + \frac{\partial}{\partial y} \left( \rho \frac{\partial v}{\partial y} \right) + \rho g_x \) |
| 2-3 | z-direction (W-momentum)                                 |                                                                                      |
| 3   | Conservation of thermal energy                           |                                                                                      |
| 3   | The concentration of species equation                    | \( \frac{\partial}{\partial x} (\rho u c) + \frac{\partial}{\partial y} (\rho v c) + \frac{\partial}{\partial z} (\rho w c) = \frac{\partial}{\partial x} \left( \Gamma \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma \frac{\partial c}{\partial z} \right) + S_c \) |

Where: \( \Gamma \) is the diffusion coefficient (diffusivity), which is given by: \( \Gamma = \frac{\mu}{\alpha} \)  
\( \alpha = \frac{\mu_{f}^2}{\nu} \) is the Prandtl or Schmidt number for the fluid.  
The terms \(-\rho u \Delta T, -\rho v \Delta T\) and \(-\rho w \Delta T\) are the turbulent heat fluxes, \( S_c \) is a source term allowing for the rate of thermal energy production.  

In this equation \( c \) is the time-mean concentration and \( c' \) is the deviation from the mean.  
The terms \(-\rho u \Delta c', -\rho v \Delta c'\) and \(-\rho w \Delta c'\) are the turbulent diffusion fluxes.
Table 2. Grill’s dimensions.

| Name                  | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|-----------------------|--------|--------|--------|--------|--------|--------|
| supply area/half room | 61*36 cm | 61*36 cm | 61*36 cm | 61*36 cm | 61*36 cm | 1.60 m² slot |
| exhaust area/half room| 61*36 cm | 61*36 cm | 61*36 cm | 61*36 cm | 170*25 cm | 170*25 cm |

Table 3. Boundary conditions.

| Name of the part       | Boundary conditions                                                                 |
|------------------------|--------------------------------------------------------------------------------------|
| Air supply             | prescribed input velocity \(u=1 \text{ m/s}\) except for case no 6 \(u=0.24 \text{ m/s}\), constant temperature \(T=20 \degree \text{ C}\), and constant water vapor \(\omega_w=0.01\) and zero concentration of contamination |
| Exhaust grill          | Zero gauge pressure                                                                   |
| Walls, ceiling, and floor | Thermally insulated, and no slip condition.                                          |
| Staff                  | Constant wall temperature \(T=34 \degree \text{ C}\), zero contamination flux, and constant water vapor flux \(q_w=4\text{E}-6\). |
| Surgical lights        | constant heat flux, on face \(q=100 \text{ W/m}^2\), and \(q=5 \text{ W/m}^2\) on the back of the lights |
| Patient                | constant wall temperature \(T=34 \degree \text{ C}\), constant contamination flux \(q_c=1\text{E}-5\), and constant water vapor flux \(q_w=2.5\text{E}-6\) |

Figure 2. Models of cases investigated for operation room.
The graphic results were plotted on the six planes named (P1, P2 P3, P4, P5 and P6) as shown in table (4). Also, CFD model validation was done by comparing with the same model result done by Son H. Ho [10]. Good agreement of CFD results is conducted as can be seen in comparison found in table (5) where maximum deviation of 6.4% was found.

| Table 4. Planes’ locations. |
| Name of plane | Parallel plane | Location | Name of plane | Parallel plane | location |
| Plane 1 | zx | y=0 | Plane 4 | yz | x=3 |
| Plane 2 | zx | y=0.2 | Plane 5 | xy | z=1 |
| Plane 3 | zx | y=0.5 | Plane 6 | xy | z=0.5 |

| Table 5. Validation. |
| Description | Son H. Ho.[10] | Present work | Deviation |
| Over all air speed m/s | 0.12 | 0.123 | 2.5% |
| Over all temperature °C | 23.2 | 21.7 | 6.4% |
| Exhaust temperature °C | 22.4 | 21.38 | 4.5% |
| Over all relative humidity | 59% | 60% | 1.7% |
3. Results and Discussions
The results obtained by applying previous mathematical and numerical procedure of present work are presented in the following figures.

3.1. Streamlines behavior
In figure 5, velocity of air, streamlines and three dimensional flow patterns are shown for all cases. In all these cases it can be seen that air enters from supply grill with its maximum velocity. Comparison between case 1 and case 2 shows that streamlines movement tends to be in smaller range and tracing semicircular path within operation room in case 2. This behavior resulted from arranging exhaust grill directly under supply grill which makes pressure force resist air movements to opposite wall. Also in case 1, it can be seen that large circular flow occurs under supply grill. Comparison between case 2 and case 3 shows that streamlines movement reach the opposite wall in case 3. The reason behind this behavior is that in case 3 the buoyancy force resist action of pressure force while in case 2 both these two forces act to move air flow down. Comparison between case 3 and case 4 shows formation of air circulation above the supply grill and low movement zone under exhaust grill. Main air movement in case 5 occurs between the supply and exhaust grills and flow circulation under supply grill, while in case 6 air flows in a like air curtains pattern.

3.2. Temperature distribution
In figures 6, 7, 8 and 9 contours of temperature distribution are shown for all cases. In order to demonstrate temperature contours inside operation room, volume sliced into some slices in xz and yz planes. These planes are defined in table (3). All these temperature figures show that temperature values are maximum at walls where heat flux exist, like staff and lights surfaces, while tend to be minimum near supply grill.

3.3. Relative humidity distribution
In figure 10, contours of relative humidity distribution are shown for all cases. In this figure, higher values appeared at entrance where they reduced gradually as delivered air moves away. Lowest values shown to appear in active zone as it appeared also in literatures such as [10]. The reason behind this phenomenon, despite there is humans in this area where they produce vapor, is that this zone has maximum temperature values. As temperature of air increases, its ability to carry vapor particles before saturation increased. This leads to reduction of relative humidity in active zone.

3.4. Contaminant concentration
In figure 11 and figure 12, contours of contaminant concentration, the most important character in present work, are shown for all cases. It can be noticed that entrance area has zero values of contaminant, which is logical since the delivered air is filtered before delivering. Zero values appeared also around working staff since boundary condition assumed particles delivered only by patient. This appears obviously as maximum particle values appear near patient's body. These particles spread upward and downward by diffusion. It is obvious that case 6 maintains minimum spread of contaminated particles in active zone. All other cases except case 5 and case 6 have serious contamination problem where particles move to working staff and cause the risk of infection during operation.

Ratios of contaminants average mass fraction in all cases taken to contaminant average mass fraction of the first case are 1.45, 0.83, 1.05, 0.61 and 0.51. This fact can be justified according streamlines behavior presented in figure 3. The worst case in these cases is case 2 because the source of contaminant exists in low movement zone so it will diffuse in operation room. While in case 1 source of contaminant exists in region where main stream separated from flow circulation. On the other hand, case 6 provides the best contaminant removal from operation room, since the streamlines behavior ensures driving contaminant directly to exhaust grill.
Case no.1  
Case no.2

Case no.3  
Case no.4

Case no.5  
Case no.6

Figure 5. Velocities and streamlines for all cases.

Case no.1  
Case no.2

Case no.3  
Case no.4

Case no.5  
Case no.6

Figure 6. Temperature contours at Plane 1 for all cases
Case no.1  Case no.2
Case no.3  Case no.4
Case no.5  Case no.6

Figure 7. Temperature contours at Plane 2 for all cases.

Case no.1  Case no.2
Case no.3  Case no.4
Case no.5  Case no.6

Figure 8. Temperature contours at Plane3 for all cases.
Figure 9. Temperature contours at Plane 4 for all cases.

Figure 10. Relative humidity distribution at plane 2 for all cases.
Figure 11. Contaminants concentration at plane 1 for all cases.

Figure 12. Contaminants concentration at plane 5 for all cases.
4. Conclusions
Careful choosing of air supply and exhaust locations arrangement is the strategy of the present work to remove pollutants from operation room. Removing these particles is important in order to prevent infection. The main conclusions were found in the current work are:

1. Using local exhaust ventilation is an important strategy that helps to get rid of contaminant before it spreads in operation room domain.
2. Using local exhaust ventilation accompanied with supplying air in a method making like air curtains is the best method to remove contaminant.
3. Using displacement ventilation is not a suitable method for removing contaminant particles because it allows particle to spread through the whole domain of operation room before leaving through exhaust grill.
4. It is necessary to make sure that the source of contaminant should not exist in low movement zone (dead zones) or region of separation of streamlines.
5. CFD simulation for different possible designs of ventilation is an important step to find out advantages and disadvantages of each design. Hence, CFD simulation study is recommended to decrease cost and avoid bad design choices that might be taken.
6. When contaminant diffusion cannot be controlled strictly, for any reason, surgical staff should use appropriate masks that ensure their safety.

| Nomenclature              | Unit                        |
|---------------------------|-----------------------------|
| C                         | Mean concentration of contaminant | kg/kg air |
| cp                        | Air specific heat           | J/(kg K)  |
| D                         | Mass diffusivity of species in air | m³/s     |
| g                         | Gravitational acceleration  | m/s²      |
| h                         | Heat transfer coefficient   | W/(m² K)  |
| k                         | Air thermal conductivity    | W/(m K)   |
| p                         | Pressure; partial pressure (with subscript) | Pa       |
| T                         | Temperature; mean temperature (with subscript) | °C       |
| u                         | Velocity                    | m/s       |
| v                         | Mean air speed relative to the body | m/s     |
| Greek letters             |                             |
| µ                         | Viscosity of air            | kg/(m s)  |
| ρ                         | Density of air              | kg/m³     |

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