Effect of air – exhaust location on surgical site particle distribution in an operating room

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Abstract. This study investigates the effect of exhaust outlet location on airflow and particle distribution in an operating room with laminar ventilation system via computational fluid dynamics (CFD). Four different exhaust opening locations and three different particle diameters (5, 10 and 20µm) are taken into consideration for the same air change rate (30 ACH). It is found that the total number of particles deposited on the operating table decreased by 64 % for the smallest particle diameter (5µm) and 26 % for the largest particle diameter (20 µm) when ceiling and floor level outlets are used together.

1. Introduction
Operating rooms have the largest risk among hygienic environments in the hospitals. During surgery, the risk of pathogen particle transition to the wound area of the patient may be originated from the surgical staff. The particle diameters which are considered as the risk of infection for the patient vary between 2.5 µm and 20 µm [1]. Furthermore, the mean value of bacteria-carrying particles (BCP) released from each staff member is 1.5 BCP/s [2]. It is important to use a well-designed ventilation system to ensure a safe and healthy environment for the patient during the surgical procedure. Nowadays, the vertical laminar air flow units are preferred in the operating rooms to satisfy this need. These systems create a unidirectional flow over the surgical site and provide to remove the pathogen particles effectively. Besides, the outlet opening position is another parameter that shapes the airflow and contaminant distributions in the operating room together with the inlet unit location. Studies in the literature generally focus on the effects of air change rate [3], surgical light area [4], unidirectional flow [5], air curtains [6] and inlet diffuser area [7] on the air distribution and contaminant removal. However, to the best of our knowledge, few studies have investigated the effect of exhaust outlet on the particle distribution in an operating room with a laminar ventilation system. The purpose of this study is to compare the air and particle distributions under various positions and numbers of air-exhaust outlet in an operating room with vertical laminar ventilation system using computational fluid dynamics.

2. Numerical Method
2.1. Geometry
In this study, an operating room that is in identical size of located in Karadeniz Technical University Hospital (Trabzon, Turkey) is investigated. The overall dimensions of the model operating room is 6.5 m (length) x 9.43 m (width) x 2.43 m (height). The operating room contains a surgical table, four surgical staff, a medical equipment, two instrument tables, a medical lamp, a laminar airflow unit (1.8 m x 2.4 m) and four air – exhaust outlets (0.39 m x 0.24 m) positioned close to the floor at each corner. The
isometric view of the model operating room and different configurations of air - exhaust outlet position are given schematically in Fig.1.

Figure 1. Geometric configuration of the operating room simulated and different configurations of air – exhaust outlet

In the study, four different air – exhaust opening positions are considered:

- Case 1: Four air - exhaust outlets at floor level
- Case 2: Four air – exhaust outlets at central level
- Case 3: Four air – exhaust outlets at ceiling level
- Case 4: Eight air – exhaust outlets at both ceiling and floor level

2.2. Numerical Model

2.2.1. Airflow Simulation Model. In numerical analysis, the Reynolds - averaged Navier Stokes equations are solved to simulate the flow field. The Realizable $k – \varepsilon$ model is used, a relatively recent development of $k – \varepsilon$ models [9]. Governing equations of the flow can be expressed in the general form as follows:

$$\frac{\partial (\rho \varphi)}{\partial t} + \nabla (\rho \varphi \vec{V}) = \Delta (\Gamma_{\varphi} \Delta \varphi) + S_{\varphi}$$

where $\rho$ is the air density, $\varphi$ symbolize the transported quantity, $\vec{V}$ is the air velocity vector, $S_{\varphi}$ is the source term and $\Gamma_{\varphi}$ is the diffusion coefficient of $\varphi$.

The above – mentioned equations are discretized into algebraic equations by the finite volume method and solved by using the double – precision solver of ANSYS Fluent 16.0. The discretization scheme used for all variables is the second-order upwind scheme. The SIMPLE algorithm is adopted to couple velocity and pressure. The Boussinesq approach is used for the change of density with temperature. The convergence criteria for all equations are set to $1 \times 10^{-5}$. The velocity inlet and outflow boundary conditions are used for the inlet and outlet, respectively. Outflow boundary condition is used to model flow exits where the details of the flow velocity and pressure are not known prior to solution of the flow problem. In the analyses, the air temperature is defined as 20 ºC and turbulence intensity is set as 10 %. The constant heat flux boundary condition is applied for surgical personnel, medical equipment, on the operating table and bottom surface of the surgical lamp. The adiabatic boundary condition and the no-slip velocity are set at all the solid wall boundaries. The enhanced wall treatment is used to solve the boundary layer on the surfaces. A grid refinement study is performed using three different grid densities (about 4 million, 6.5 million and 9 million), resulting in $1 \leq y^* \leq 7$ for the entire computational domain. As results of agreements on air velocity and particle concentration distributions of 6.5 and 9 million cells, 6.5 million cells are preferred in the analysis.
2.2.2. Numerical Model of Particle Motion. In this study, the Lagrange approach is used to calculate the time dependent momentum equation for each particle. The related equation is expressed as follows:

\[
\frac{d\mathbf{u}_p}{dt} = F_D (\mathbf{u} - \mathbf{u}_p) + \frac{g (\rho_p - \rho)}{\rho_p} + F_a
\]

(2)

where \( \rho_p \) and \( \rho \) are particle and air density, \( \mathbf{u} \) and \( \mathbf{u}_p \) are the velocity vector of the air and particle, respectively and \( g \) is the gravitational acceleration; \( d\mathbf{u}_p/dt \) and \( F_D (\mathbf{u} - \mathbf{u}_p) \) represent the inertial and drag forces, respectively. The term \( F_o \) is the inverse of the relaxation time and \( F_a \) is the additional terms such as the Saffman’s lift force, thermophoretic force and Brownian force [10].

The discrete random walk (DRW) model is used to simulate dispersion of particles due to turbulence. After the turbulent airflow area is analyzed, particles are injected to the flow domain from the mouth of the surgical staff. The escape boundary conditions are set for the particles leaving the OR via outlets, and trap boundary conditions are considered for all the other solid surfaces. Trap boundary condition implies that the particles that will come into contact with the surfaces will not resuspended by air.

2.2.3. Verification of Mathematical Model. To validate the numerical models, we used the results of the experimental study conducted by Zhang and Chen [11]. The model room dimensions are L x W x H = 4.8 m x 4.2 m x 2.4 m. The air is supplied at a total flow rate of 340 m³/h with two inlet grills located on the floor. Six lamps placed on the ceiling and four human simulators located on the floor are used as the heat sources. Particles with an average diameter of 0.7 µm are released into the airflow domain from a point source installed 0.3 m on the floor (\( x = 1.5 \) m; \( y = 2.1 \) m; \( z = 0.3 \) m).

![Figure 2. Comparison of simulated and measured velocity and temperature profiles at three different locations; (a) velocity, (b) normalized temperature \( T = (T - T_{supply})/(T_{exhaust} - T_{supply}) \)]
In Fig. 2, the velocity - temperature profiles (V1, V3, V5) at three different locations are compared with experimental data [11]. The simulated velocities are in agreement with the measured data. The difference in temperature profiles could be ascribed to the insufficient information of boundary conditions. However, in the experimental study, the temperatures in the walls may not remain constant. In the simulation study, uniform temperature profiles are applied for the wall boundary conditions. Fig. 3 compares the simulated particle concentration with experimental data at P1, P3 and P5. As shown in the figure, particle concentration values display significant changes at three different locations. This behavior can be explained by the inadequate information of boundary conditions and the known lack of the DRW model. The DRW model may show a tendency for small particles to concentrate in low – turbulence regions in strongly nonhomogeneous diffusion-dominated flows [12].

3. Results and Discussion

Figure 4 shows the velocity contours and streamlines in the center plane of the operating room for different outlet opening arrangements. Airflow distributions over the operating table present similar behaviors but completely different air flow patterns and air velocity magnitudes are observed for the rest of the operating room. It is noticed that the surgical light restrains the development of air flow, and a stagnant area is modified below the operating light in all the cases studied. Depending on the outlet configurations, there are also several recirculation regions formed in different sizes at different locations of the room. Regardless of the outlet configurations, the recirculation regions on the upper left corner and on the left of the operating table preserve their presence. These recirculation fields are undesirable flow structures for controlled environments in terms of their ability to host particles for long period of times.

Figure 3. Comparison of simulated and measured particle concentration profiles at three different locations

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Figure 4. Velocity-contours and streamlines at the center-plane of the operating room; (a) floor level, (b) central level, (c) ceiling level, (d) floor – ceiling level
Particle mass concentration contours of the 20 µm particles on the surgical table level are given in Fig. 5. It is seen that the highest concentration values are generally obtained on the operating table and in the regions close to the head and end of the table. Regarding to the outlet position and number, the concentration distribution shows different variations on the plane of the surgical table height. It can be stated that in the case of floor level-outlet (Case 1), particles are generally intensified in a limited area in the proximity of the operating table. However, in other cases (Cases 2-4), the contaminant distribution is observed on the left side of the plane away from the table. Furthermore, it can be noted that a particle free area is obtained on the table for the same cases. For a more quantitative evaluation, the number of particles deposited on the operating table defined as the critical region is compared.

Figure 5. Particle concentration on the height of surgical table (y=1 m) for 20µm; (a) floor level, (b) central level, (c) ceiling level, (d) floor – ceiling level

Figure 6 shows the amount of particle number deposited on the surgical table for four different air – exhaust opening locations and three different values of the particle diameter. As expected, due to increasing gravitational forces, the particle number deposited on the table is increased as the particle
size range is increased. Similar behavior is observed regardless of the outlet location and number. It is figured out that the highest deposition on operating table is acquired with the outlets located close to the floor level while the lowest deposition is reached when the eight outlets close to the floor and ceiling levels are employed. The amount of particles deposited on the operating table in the floor – ceiling exhaust opening position decreases by 64 % for the smallest particle diameter (5µm) and 26 % for the largest particle diameter (20 µm). As a result, it can also be noted that smaller particles are more sensitive to the change of outlet arrangements.

4. Conclusion
In this study, the effect of outlet position and number on airflow and particle distribution in an operating room are investigated numerically. The Realizable $k−\varepsilon$ turbulence model is applied to handle with air flow distribution. The Lagrangian tracking scheme is used to calculate the particle trajectories originated from the mouth of the surgeries. The velocity contours and streamlines, concentration distribution on the table level and amount of particles deposited on the operating table are calculated and compared for different outlet arrangements. The main concluding remarks are listed below:

- Regarding to the outlet arrangements, airflow distribution in the projection of the LAF unit present minor differences while completely different air flow map is observed for the rest of the room.
- In the case of floor level outlet, the distribution of pollutants is limited to a certain area. A wider spreading is seen for other cases especially in the direction of closer outlets.
- The lowest particle deposition number is obtained with the use of outlets both in the floor and ceiling levels.

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