

Influence of air velocity on indoor environment quality in unidirectional flow operating theatres: A study based on Computational Fluid Dynamics

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Abstract. It is necessary to characterise air-conditioning airflow in order to optimize hospital Indoor Environment Quality in high-performance operating theatres, and also reduce the risk of nosocomial infection due to pathogen contamination. The aim of this article is to study the prevalence of optimal healthy conditions from controlled air flow quality in hospital facilities, and to minimize energy consumption. To this purpose, the indoor air movement was modelled by Computational Fluid Dynamics technology. The optimal results showed that it is necessary to drive ultra-clean air ranging between 0.25 m/s and 0.40 m/s, values which are adequate to perform efficient sweeping and cleaning of the air near the patient, maintaining unidirectional air flow permanently as the air passes through the surgical field. These speeds must be taken into account as calculation parameters in new hospital facility projects, and as control parameters for the existing operating theatres.

1 Introduction

Healthcare-associated infections are among the most common and harmful causes of unintended harm to health care. European Commission studies confirm that it is possible to reduce these adverse effects by 20% per year, as infection control methods are not optimized. Approximately, 37,000 deaths annually are caused by nosocomial infections. That is why the European Parliament is developing a Legislative Project against hospital contagion [1].

In Spain, prevalence of patients with nosocomial infection, contracted during his or her stay in hospital, was 7.74% in 2017, about 25% of which was caused after underwent a surgical intervention [2].

Air-conditioning of healthcare buildings is one of the most complex installations that Hospital Engineering has to deal with [3]. Hospital areas are very different each other, both technical requirements of facilities and type of services they must provide, specially respect of Indoor Environment Quality (IEQ) and thermal comfort. Furthermore, characteristics of supply air and its movement along the room allow cleaning of airborne pathogens. Air-conditioning systems are therefore an effective way to control infection in hospitals caused by airborne bioparticles.

IEQ has great importance in operating theatres, as there are sources of indoor infection that can contaminate the room and so reduce IEQ level: medical personnel, patients, equipment, instruments, etc. Moreover,

movement of personnel and instruments causes spread of airborne pathogens [4, 5]. Air-conditioning is the key tool for achieving adequate IEQ, which must keep the number of airborne bioparticles present below reference values as they are the vehicle for spreading disease [6].

Intensity of infection [7] is proportional to concentration of infectious airborne bioparticles and the time of exposure to them. It is therefore crucial that number of air changes per hour is sufficient to ensure a low concentration of bioparticles in the environment and to minimize air age in the room.

García Sanz-Calcedo and Monzón González (2014) analysed the economic impact of applying measures to guarantee environmental biosafety on health building construction projects. They checked that measures minimized impact on workers' and patients' health in refurbishing of health centres in Extremadura (Spain) [8]. Operating theatres are part of hospital's clean rooms. Heating, ventilating and air-conditioning (HVAC) system for operating rooms should protect the room against cross-contamination [9]. Overpressure conditions provided to the room will prevent it. An overpressure value of 20 Pa will be enough, allowing Ultra Clean Ventilation (UCV) system to work optimally avoiding the entry of pathogens from adjacent areas. Lydon et al. (2014) observed the effect of opening and closing doors in two pressure scenarios (0 Pa and 20 Pa) with respect to adjacent spaces [10]. The results concluded that the UCV system operates efficiently with positive pressure (20 Pa) but fails when

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there is no pressure difference between the operating room and surrounding areas.

Tinker and Roberts (1998) applied Computational Fluid Dynamics (CFD) technology to characterize the air-conditioning system of a hospital operating room in the United Kingdom [11]. These authors concluded that a thermal plume is generated by thermal radiation from surgical lights. This is only noticeable when airflow passes through them below the critical velocity value. Critical velocity value will be 0.10 m/s, since with a velocity greater than 0.3 m/s, the formation of such natural convection currents is not detected.

Ventilation of an operating theatre is performed by imposing a number of air changes per hour or, what is the same, a fresh from outside air flow per volume unit. However, this parameter does not ensure that ventilation will achieve indoor air quality throughout the room, as design of the ventilation system may result in by-pass between supply and exhaust, backwater areas, etc.

In addition, number of real air renovations executed should be used to evaluate performance of a ventilation system. This parameter quantifies the air residence time at all points of the room to be homogeneous [12]. Equalizing number of renovations carried out to those planned and reducing average air age in the room improves the efficiency of the HVAC system. Therefore, ventilation will be adequate when it is possible to move the driven air evenly throughout the room, avoiding problems of bypass or backwash. Moreover, minimizing air fresh flow to promote energy efficiency. In order to achieve adequate ventilation with minimum fresh air flow it is necessary to achieve maximum ventilation efficiency.

Quantifying the efficiency of air conditioning is no easy process as it depends on the flow pattern, room geometry, layout of the drive and extraction, etc. This is why the CFD is used. Analysis using CFD technology allows an in-depth study of the complex airflow generated in operating theatres. That is, their movement pattern and fluid property distributions (air age, temperature, pollutant dispersion, etc.). They are thus a virtual trainer for the optimisation of ventilation systems [13].

The aim of this study is to carry out an analysis of IEQ achieved in a high-performance operating theatre for different air supply velocities from central air diffuser. Results will make it possible to calculate an appropriate velocity air supply to design new HVAC installations in hospital operating rooms, valid also as a control parameter of existing.

2 Methodology

CFD technology was employed to calculate air velocity profile in two interesting areas: at patient's level and over surgeon's head.

Range of simulated air velocities is found in reference literature as recommended for this application [4]. UNE 100713:2005 also defines a recommended range of

values. An operating theatre with typical dimensions and characteristics of this type of theatre was modelled. The arrangement of extraction grilles is also the usual one in operating theatres of this type, since the same extraction duct is used for the grilles in the lower part of the wall and for the grilles in the upper part.

Firstly, control volume of the system, i.e. the computational domain, was defined. Geometry of the room has the typical dimensions of European operating theatres. The modelled geometry (Fig. 1) presents six boundary planes, whose names are: floor, ceiling and wall i ($i = 1-4$), were defined with the condition "wall" and applied the physical characteristics to be affected by the heat transmission. The room has a square floor plan of 6.00 m on each side and a height of 2.85 m. It has a square central diffuser of 2.50 m on each side, centred on the ceiling of the operating room. All extraction grilles have dimensions of 0.30 m × 0.15 m and are located 0.15 m from the nearest perpendicular surface. There is a separation of 1.00 m between them and up to the side walls. The model has two doors facing each other, 1.60 m wide and 2.05 m high. Door openings were modelled as a 2 mm free space at the sides and 4 mm at the top and bottom.

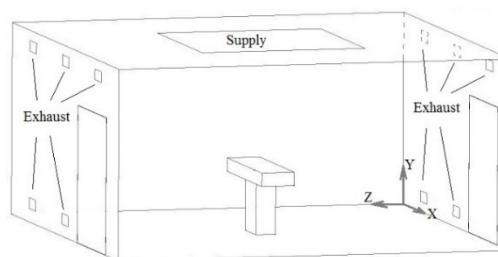


Fig. 1. Geometry of the computational domain.

Spatial discretization of the control volume, i.e. the meshing of the geometry, was established. The meshing generates a series of small volumes called cells, inside of which they house the nodes, on which the calculations will be made. Distribution of cells, their shape and size are determined from the mesh consistency study described in the results section. Five cases were raised that present enormous differences in the characteristics of the mesh. Table 1 shows these characteristics.

Table 1. Spatial discretization characteristics.

Case	No. cells
01	1,248,712
02	1,845,340
03	2,486,754
04	4,450,604
05	7,811,099

It is checked that the values of the results are similar and therefore the consistency of the mesh is validated. The number of cells and the characteristics of Case 03 was used to carry out our studies. This is because it provides a consistent fluid field solution with the lowest possible computational cost.

IEQ was assessed in terms of air velocity profiles generated at the head height of medical personnel present and over the patient. For this purpose, a stationary calculation scheme has been proposed which will provide stabilized value for an infinite time of the velocity magnitude.

In the computational domain, conservation laws are established as equations of fluid field government. The equation of conservation of mass applied to steady state study is given by Equation (1):

$$\nabla \mathbf{u} = 0 \quad (1)$$

The equation of conservation of momentum is given in Equation (2). For its definition, it has been taken into account variation of the fluid density according to the approximation proposed by Boussinesq (term β). According to the Boussinesq Model, the consequences of this variation in density are simplified and will only affect the conservation equation of momentum.

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g} \beta (T - T_{ref}) \quad (2)$$

The energy conservation equation taking into account that there are no internal sources of heat generation is given by Equation (3):

$$\rho c_p \mathbf{u} \cdot \nabla T = k \nabla^2 T \quad (3)$$

The Reynolds-Averaged Navier-Stokes (RANS) approach is used to resolve the fluid field. In the case of a stationary study, continuity is verified through Equation (4), since the partial time derivative is simplified.

$$\frac{\partial}{\partial x_i} (\rho \mathbf{u}_i) = 0 \quad (4)$$

Considering the viscous and incompressible fluid, the momentum equations can be written in their compact form as in Equation (5). They can be written in Cartesian tensor form as follows:

$$\begin{aligned} & \frac{d}{dt} (\rho \mathbf{u}_i) + \frac{d}{dx_j} (\rho \mathbf{u}_i \mathbf{u}_j) = \\ & = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} \right) - \rho \mathbf{u}'_i \mathbf{u}'_j \right] + S_i \end{aligned} \quad (5)$$

where ρ is the density and μ is the viscosity of the fluid, t is the time, x_i will represent each axis of the coordinates system, \mathbf{u}_i are the components of the velocity vector and S_i is the source term.

Standard k- ϵ model was employed to model turbulence in fluid field and Boussinesq hypothesis was used. This hypothesis uses Reynolds stress tensor with the mean velocity gradients indicated in Equation (6):

$$-\rho \mathbf{u}'_i \mathbf{u}'_j = \mu_t \left(\frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \frac{\partial \mathbf{u}_i}{\partial x_i} \right) \delta_{ij} \quad (6)$$

where μ_t represents turbulent viscosity, k is the turbulent kinetic energy and δ_{ij} is Kronecker Delta.

This implies solving two more equations. It concerns turbulent kinetic energy equation, k , and turbulent kinetic ratio equation, ϵ .

The method of two standard equations k- ϵ [14] was chosen as turbulent closing model. As a complement, it has been combined with the Standard Wall Functions which implement the Universal Wall Law. These are suitable when the fluid has negligible pressure gradients, as occurred evaluating HVAC systems applied to operating rooms.

An air velocity supplied through the large central diffuser were defined as boundary condition with negative Y-direction. Drive velocity magnitude varied from 0.10 m/s to 0.40 m/s, at 0.05 m/s intervals. Thus, there was seven case studies. Each of the velocity magnitude values will generate a different flow rate value. A forced extraction will then be applied to each of the 10 grids in the room. The value of the extract flow rate is calculated as a proportion of the total impulse flow rate. The values for the impulsion and extraction conditions of each study are shown in Table 2. Finally, the apertures of the doors are defined as free outlets at atmospheric pressure and the rest of the surfaces as "wall" ($u_x = u_y = u_z = 0$).

Table 2. Volumetric flow rate of impulsion and extraction.

V (m/s)	Q driven (m ³ /h)	Q extracted (m ³ /h)
0.10	2,250.00	2,025.00
0.15	3,375.00	3,037.00
0.20	4,500.00	4,050.00
0.25	5,625.00	5,062.50
0.30	6,750.00	6,075.00
0.35	7,875.00	7,087.50
0.40	9,000.00	8,100.00

The fluid characteristics are considered constant except for the density, which is considered a variation according to the Boussinesq approximation, to take into account the buoyancy term in the momentum equation. For the reference temperature of $T_{ref} = 20^\circ\text{C}$ (293.15 K), the value of the fluid variables are as follows: $\rho = 1.225 \text{ kg/m}^3$, $\mu = 1.8 \cdot 10^{-5} \text{ kg/m}\cdot\text{s}$, $c_p = 1004 \text{ J/kg}\cdot\text{K}$, $k = 0.026 \text{ W/m}\cdot\text{K}$ y $\beta = 0.0034 \text{ K}^{-1}$. The wall characteristics are the following: $\rho = 1200 \text{ kg/m}^3$, $c_p = 1500 \text{ J/kg}\cdot\text{K}$, $k = 0.3 \text{ W/m}\cdot\text{K}$. Characteristics applied to the operating table are: $\rho = 2720 \text{ kg/m}^3$, $c_p = 871 \text{ J/kg}\cdot\text{K}$, $k = 202.4 \text{ W/m}\cdot\text{K}$.

For each simulation, the flow governing equations are solved, considering the initial and boundary conditions imposed, using the algorithm proposed by the Finite Volume Method. The ANSYS Fluent software configured with Pressure-based solution technology is used to execute it. The Coupled method is employed to solve the finite system of algebraic equations. The way it solves velocity and diffusion gradients will approximate by the Least Square Cell Based order which is suitable for unstructured meshes. The pressure is solved by the

Pressure Staggering Option (PRESTO). Finally, a second upstream approximation, 2nd Order Upwind, is applied to solve the momentum equation, the turbulent kinetic energy equation and the turbulent kinetic energy dissipation rate equation.

3 Results

This section shows the results for mesh consistency study and for air velocity profiles study over medical personnel and patients present in the room.

For mesh consistency study, five cases with different mesh characteristics were solved. Number of elements, density and shape and size of the cells were varied for mesh consistency study. Carrying out simulation were obtained results shown in Table 3 for each case studies.

Table 3. Results of meshing consistency study.

Case	No. cells	Pressurization (Pa)
01	1,248,712	95.86
02	1,845,340	37.80
03	2,486,754	34.95
04	4,450,604	35.42
05	7,811,099	35.12

These results are represented graphically in Fig. 2. A high correlation is shown between the values resulting from the proposed studies. For different values of the number of cells, a similar result is obtained for the variable of interest: the pressurization of the room. This means that the mesh provides a consistent solution.

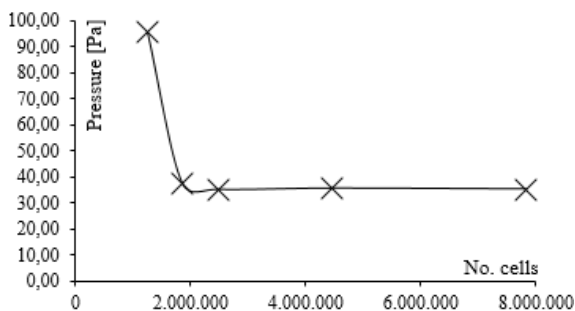


Fig. 2. Grid independence study.

Fig. 3 shows the air velocity profile generated by each of the different study supply velocities. This profile is established on a horizontal line located at a height of 1.75 m and which crosses the room through the median plane in the direction of the Z-axis. Represents the air velocity profile to which the medical personnel present in the operating room will be exposed.

Fig. 4 shows the air velocity profile generated by each of the air velocity magnitudes proposed for the study. In this case, they are those established on the horizontal line situated at a height of 1.20 m and which crosses the room through the median plane in the direction of the X-axis. These are the different profiles to which the patient will be exposed according to the velocity of impulsion chosen in the diffuser.

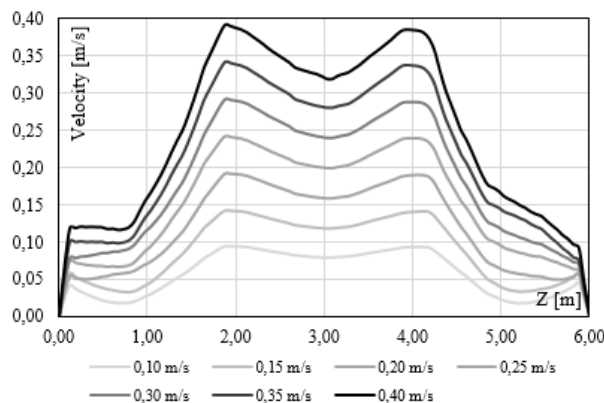


Fig. 3. Air velocity profile over medical personnel (Y=1.75 m).

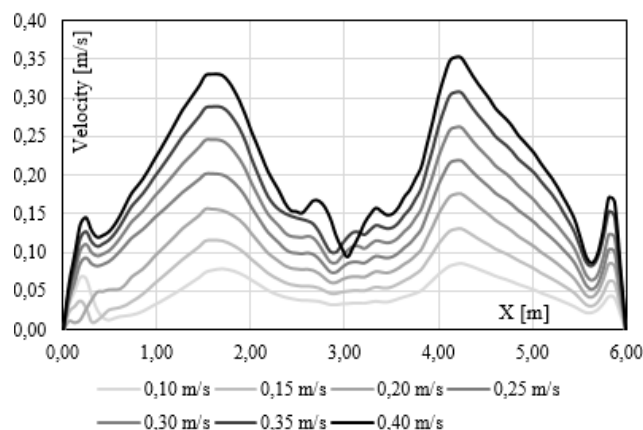


Fig. 4. Air velocity profile over lying patient (Y=1.20 m).

4 Discussion

Results show that CFD technology is a suitable tool for designing operating theatres, as it ensures proper ventilation quality and minimizes the risk of nosocomial infection by optimizing energy and environmental costs. Air must be driven at a speed that favours unidirectionality to facilitate high levels of cleanliness and low levels of turbulence. These characteristics minimize the presence of pathogens in the surgical field. A diffuser surface large enough to cover the entire surgical field is also necessary.

To ensure unidirectionality, the key parameter is the ultra-clean supply air velocity. Factors that can interrupt the unidirectionality of the flow are: low supply air velocity and thermal contour generated around equipment or people due to thermal radiation. These thermal contour will induce a flow of air called natural convection.

In healthcare applications, medical requirements take precedence over the comfort of people in terms of the drive air velocity [15]. In this way, a high drive air velocity can be annoying for comfort of people, but is necessary for cleaning the surgical field.

It was also observed that driving ultra-clean air with a velocity less than 0.10 m/s will cause it to reach the head of medical personnel with values below the critical value of 0.10 m/s. There are also additional values of drive

velocity that reach the patient at a speed of less than 0.10 m/s. This is even more critical, as the patient is required to be as unidirectional as possible.

Regular monitoring of these critical parameters is essential to assess efficiency of air control and to detect the irregular introduction of airborne particles into the air through clothing of medical personnel or transport of medical materials [16].

An adequate maintenance policy for operating room facilities is an effective tool for ensuring staff and patients' safety at hospitals [17].

5 Conclusions

It was verified that drive velocities below 0.25 m/s reach the operating table with a speed below 0.10 m/s. This means that impulse velocities that are equivalent or lower than this value are ruled out as they will not maintain unidirectional flow through the surgical field.

It was found that drive velocity values over 0.25 m/s are suitable for this application. However, it is recommended a value higher than 0.40 m/s, so that it reaches the surgical field at 0.15 m/s. This value avoids air flow turbulence within the surgical field.

It was observed that air discharge velocity of 0.40 m/s was suitable for sweeping and cleaning the surgical field thoroughly, although the air velocity at the head height of the medical personnel was still high between 0.30 m/s and 0.35 m/s. Therefore, it is recommended a velocity of 0.40 m/s for safety of the patient.

The authors wish to acknowledge to the Junta de Extremadura, and European Social Found (FEDER) for the support of this research work. This study has been carried out through the Research Project GR-18029 linked to the VI Regional Plan for Research, Technological Development and Innovation from the General Government of Extremadura 2017–2020.

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