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Numerical and experimental analysis of airborne particles control in an operating theater

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ABSTRACT

The design of a ventilation system for operating theaters (OT) is aimed to reduce the patient infection risk while maintaining adequate comfort and productivity for the surgical staff. Nowadays, Computational Fluid Dynamics (CFD) represents an important tool to simulate the airflow pattern in an operating theater and its ability to remove airborne particles. The CFD advantages, compared to experimental campaigns, consist in the ability to test different configurations, in the ease of implementation and in time and money savings. The aim of this work is to numerically and experimentally investigate an OT with a layout according to the Standard DIN 1946-4. Moreover the effectiveness of a differential airflow diffusion system on reducing the particle concentration above the operating table is analyzed. The supply air comes from a ceiling filter system composed of 23 H14 filters, which assures an unidirectional flow with differential air velocities over the protected area. In order to experimentally evaluate the performance and the protection grade SG, according to DIN 1946-4, and to validate the numerical results, a measuring campaign has been carried out within a laboratory setup of an OT. Two different scenarios have been adopted to evaluate the protection level against the entry of external and internal contaminant loads into the protected area. For both cases, the simulated and measured particle concentration in the protected area agree well, and the differential air flow diffusion system is able to maintain the desired protective effect (SG) against contamination load in both the design and the off-design conditions.

1. Introduction

The design of a ventilation system for an Operating Theater is aimed to prevent the risk of infections during surgical operations, while maintaining an adequate comfort condition for the patient and the surgical staff [1]. Surgical Site Infections (SSI) typically occur on site during an operation [2]. They are found to be associated with increased postoperative length of stay, increased costs, hospital re-admission rates and the use of antimicrobial agents [3]. The interest to intervene in a significant way to reduce the sources of these contingencies is obvious. There are many aspects that could influence these type of infections: factors related to the patient (as the susceptibility to infections), factors related to the surgical site and others related to the ventilation system of the OT environment. The contamination on surgical site is an unavoidable reason for the occurrence of SSIs. Primary sources of contamination in OTs are airborne particles (biologically active or inert) released by the human body during normal activity [4]. Their diameter size varies typically between 0.5 and 10 μm and their settling on the surgical site could be the cause of potential infections [5]. A surgeon during activity may release about 1000 airborne particles/min [1], while the patient is not usually a significant contaminant source because its movements are minimal [6]. Moreover, the beneficial use of surgical face masks has yet to be conclusively demonstrated [7]. The works of Stacey et al. [8], Charneley [9], Whyte et al. [10] and Lidwell et al. [11] have shown the important correlation between the airborne wound contamination and the ventilation system. In particular, they have established a linear relationship between the level of bacterial air contamination and the frequency

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of "deep sepsis" following surgery operations. Therefore, a proper ventilation system is crucial in OT environments. These can be considered as special cleanrooms where different types of processes (operations) are carried out by different personnel (medical staff). As a consequence, many national and European standards, which deal with operating theaters and related controlled environments, have common roots with the standards and procedures used in cleanrooms, as the ISO 14644-1 [12] for airborne particle contamination and the ISO 14698 [13] for microbiological contamination. In the last years many national standards and technical reports have been issued with the aim to rule the design and the performance test procedures of operating theaters from the point of view of airborne contamination control. However, there is no complete consensus and uniformity among the various standards. The performance tests for airborne particle contamination in OTs are quite time consuming and expensive. Moreover, availability, reliability and cleanliness are important parameters for OTs, especially in emergency cases. Therefore the time available for carrying out real contamination and ventilation performance tests is always short and, as often occurs, practically null. The advantages of using CFD are many. It is cheaper and less invasive than the traditional experimental test campaign and it allows to investigate different solutions and case scenarios without interfering with the normal operation of an OT. Therefore, it may be a useful tool for the design, testing and the comparison of ventilation performances of existing OTs or new ventilation alternatives [14]. Several CFD studies of indoor ventilation systems have been already carried out. Swift et al. [15] have discussed the impact of different air distribution strategies on infection control and the effects of lightings and obstructions on unidirectional air flow systems. Numerical simulations on a vertical and a horizontal laminar airflow distribution in OT have investigated their impact on the bacteria-carrying particle distribution, even though a complete experimental validation has not been carried out [2]. Memarzadeh and Manning [16] have used CFD to show that, when the design is appropriate, unidirectional flow conditions are the best choice for controlling the risk of contaminant deposition in a surgical operating room. Memarzadeh and Jiang [17] have numerically investigated the impact of the ceiling height on the level of contaminants present at the surgical site in an operating theater. Kameel et al. [18] have numerically evaluated the airflow regimes, relative humidity and heat transfer characteristics under actual OT's geometrical and operating conditions. Brohus et al. [19] have investigated the influence of two disturbances in an operating room: the door opening during an operation and the activity level of the staff. The same study has also been carried out by Shuyun et al. [20], and Tung et al. [21] for the specific application in local operating theaters.

The accuracy of OT's CFD simulations strongly depends on the considered obstacles in the domain, e.g. human occupants and medical equipment, as well as on the appropriate settings of boundary conditions and numerical simulation parameters, such as contaminant sources and heat fluxes, as demonstrated by Srebric et al. [22] and [3]. All these previous works have been validated through comparison with experimental data, even though they have only treated downward laminar (unidirectional) airflow with HEPA (High Efficiency Particulate Air Filter) filtered air at uniform velocity. On the contrary only few works have dealt with the application of CFD simulations to national standard performance tests on air contamination control [23–27]. Traversari et al. [28] have evaluated the airborne bacterial contamination in an OT by comparing two air diffusion systems, i.e. a unidirectional horizontal flow (UDHF), and a unidirectional downward flow (UDDF), partly using the procedure described in standard DIN 1946-4 [27].

The present research work is aimed to numerically and experimentally evaluate the airflow, temperature and airborne particles distribution of an OT in "operational conditions" with a layout according to the German standard DIN 1946-4 [27]. Moreover the effectiveness of a differential air diffusion system in reducing the particle concentration in the surgical zone close to the operating table is investigated. The supply air comes from a ceiling filter system composed of 23 H14 filtering units, which assures an unidirectional flow on the surgical table and close to the staff area. The configuration of the operating theater and the procedures for the experimental test of the protection grade SG are chosen in accordance with the German standard DIN 1946-4 [27], while the ISO 14644-1 [12] are used for the ISO N class evaluation. The aim of the protection grade SG is a quantitative evaluation of the level of protection provided by an OT ventilation system against the entry of external and internal particle contamination loads into the protected area, taking into consideration airflow pattern obstacles and heat loads. The German standard DIN 1946-4 [27] has been chosen because it presents a complete and appropriate test procedure for evaluating the performance of a ventilation system in an operating theater with respect to airborne particle control at operational state (simulated conditions).

2. Case study

The plan dimensions of the operating theater used as case study are of 7 m, with a net height of 3 m. The theater is provided with a unidirectional ceiling diffuser composed of 23 terminal HEPA H14 filters (each with a net area of 0.521 m $\times$ 0.521 m) installed in a plenum of 3 m $\times$ 3 m. The main characteristic of this ceiling filter system is the differentiation of the supply air velocity. Indeed, as shown in Fig. 1, the three central terminal filters, located above the operating table (Fig. 2) and labeled High Speed (HS) filters, release air at a velocity of 0.45 m/s, while the six Medium Speed (MS) filters around them release air at a velocity of 0.35 m/s. The periphery of the ceiling diffuser is equipped with H14 filters with a low air speed value (LS) equal to 0.25 m/s.

At each corner of the OT, two extraction grilles are installed, as shown in Fig. 1. Two led-based scialitic lamps are positioned in the ceiling, facing the operating table in the middle of the OT (see Fig. 1). The ventilation system of the OT is designed to ensure an ISO 5 class in 'operation occupational state', conforming to the ISO 14644-1 [12]. In order to respect the limitations in terms of air quality and contamination control, 6791 m^3/h (or 45 Air Changes per Hour - ACH) of air is injected from the ceiling filters. Of these, 2500 m^3/h (or 17 ACH) is fresh air while the rest of the airflow rate was recirculated. In order to avoid the risk of contaminant infiltrations from adjacent environments (e.g. ancillary rooms and corridors), an overpressure of 15 Pa is maintained in the OT by extracting 6600 m^3/h of air (or 47 ACH), while 191 m^3/h flows out through the main and service doors, that have a permanent open slit of 5 mm along the side close to the floor. The supply air at the ceiling filters has a design temperature of 20 °C and 50% relative humidity.

3. Computational model

Steady state numerical simulations have been carried out using Ansys© FLUENT 14.5.7. The 3D computational domain of the OT case study has been discretized with an unstructured mesh, made of tetrahedral elements. A grid independence study has been carried out with two different grid sizes, resulting in 5.5 $\times$ 10^6 and 10 $\times$ 10^6 cells. The mesh refinements have been applied in the regions with the highest gradients of transported quantities, i.e. air inlet, air outlet, and especially below the ceiling diffuser, in order to capture the main flow and heat transfer features. No differences in the results could be appreciated between the two meshes. The non-