Operating room ventilation with laminar air flow ceiling and a local laminar air flow system near the operating table for the patient

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Abstract. The aim of this study is to determine how the air flow from a unidirectional air flow (UAF) system and a local ventilation system will interact with each other. The study analyzes the air circulation near the operating table at different air flow velocities from both systems. The air flow velocities correspond to the usual range of velocities that are recommended by norms and guidelines. The research was approached by numerical and experimental studies. The thermal plume of the patient was measured by Particle Image Velocimetry (PIV) and thermography (IR) and compared with the results from the numerical case. A mesh independency study was made for the numerical case. The study showed that velocities \( \geq 0.2 \text{ m/s} \) from the UAF, depending on the height of the room, can overcome the thermal plume generated by a human subject with a moderate activity (100÷120W). The velocities from the local ventilation system need to be higher with at least one step, in accordance with the distance from the ventilation system to the operating wound, in order to avoid disturbances generated from the UAF system.

1. Introduction

The operating rooms (ORs) have an essential role in the modern society. Since the time of Florence Nightingale (mid 1860) [1, 2] and Joseph Lister (1870) [3], hospital rooms were thought as „spaces that do no harm to the occupants” [4]. Due to the technical evolution and the necessity of having a clean environment in many fields, including the medical field, the concept of „clean room” started in the 1950s [1-4] and more intense over the 1960s [5-7]. From that time, ORs have been classified as clean rooms and they tend to evolve along with the medical and technological field. The complexity of the ORs have been studied over time by numerical and experimental approaches, establishing classification criteria that are strong correlated with the ventilation system and the activities that take place there. In the modern OR, the most common ventilation strategies consist in a unidirectional air flow (UAF) plenum, also known as laminar air flow (LAF) plenum, with outlet diffusers on the lateral walls or in the corners of the room. Another ventilation strategy that can be seen in ORs with low requirements of cleanliness, or that have a low budget, is a mixed ventilation system with 4-way diffusers in the ceiling and outlet diffusers placed in the same configurations presented previously. One common issue with the ventilation strategies in the ORs is the impossibility of the treated and filtered air to overcome the thermal plumes [8, 9] generated by the occupants and the medical equipment’s, so that it can reach the area of interest (patient and operating table), in order to reduce the intra-operative infections, also called nosocomial infections [10]. Another common problem, just as important as the previous one, is the inability to achieve an acceptable thermal comfort for all occupants in the OR [11, 12]. Besides these two problems, there is another topic of interest that refers to the large energy consumption of such ventilation systems. The high energy consumption is due to the high air changes per hour recommended...
in the existing norms worldwide[13-15]. The general goal of this study is to determine how the air flow from a unidirectional air flow (UAF)[16] system, also known as laminar air flow (LAF)[17] system, and a local ventilation system, similar to a mobile laminar air flow (MLAF)[18-21] system, will interact with each other. The study analyses the air movement near the operating table at different air flow velocities from different systems. The air flow velocities correspond to the usual range of velocities that are recommended by norms and guidelines [13, 14, 22, 23]. The research was conducted using numerical and experimental studies. The numerical model has been validated using experimental data. The experimental measurements were made in a climatic chamber which simulates a real scale OR. The OR geometry of the numerical model is identical with the climatic chamber from the laboratory, where the measurements were conducted. In the numerical model was added also a MLAF ventilation system near the patient’s head. This study is a precursor to a more complex study regarding this subject.

2. Methods
2.1 Experimental
The experimental campaigns were carried out in a climatic chamber that allows the adjustment of the temperature for each wall, including floor, ceiling and door. The wall temperatures were set at approximately 24°C. The climatic chamber simulates an OR at real scale and has a ventilation system with UAF diffuser and lateral diffuser as outlets. The dimensions of the climatic chamber are 3.5x3.5x2.5m (lxLxH). Particle image velocimetry (PIV) measurements were made for determining the velocity profiles of the thermal plume and infrared thermography (IR) measurements were made for determining the gradient temperature of the thermal plume. The time interval between two laser beams was 1500µs, capturing 500 images for each measurement. A sketch with the equipment used and their placement can be seen in Figure 1 (1 - CCD camera, 2 - double pulsed laser, 3 - laser unit, 4 - multiplexer, 5 - external command panel, 6 - PC, 7 - smoke generator, 8 - compressor, 9 - manikin, 10 - UAF).

![Figure 1. Equipment placement for the PIV measurements, patient thermal plume](image-url)

A thermal manikin placed as a patient, on an operating table, was used in the measurement campaign to simulate the natural heat release by convection, which is also known as thermal plume[8, 24]. The thermal manikin had different temperatures for each segment of the body (head, core, arms, legs), temperatures that are normal to a healthy human subject (34°C – head, 32°C – core, 30°C – arms, 27°C – legs). The manikin was placed under a UAF system, in the center of the room. The dimension and the placement of the manikin in the OR are identical in both studies (numerical and experimental). The thermal manikin used to simulate the patient is presented in detail in a previous article [25]. As a brief presentation, its working principle is to control the surface temperature of each individual zone and to record the electrical power consumption as an indication of the thermal state of the zone. The manikin is controlled through a dedicated software interface which allows user to specify set-point values for each surface temperature of the 79 zones. Monitoring system can log the evolution of temperature for a total of 395 available sensors and record the electric power consumption of each segment. The assessment of the thermal sensation is made using the equivalent temperature (t_{eq}) index as presented in the standard EN ISO 14505/2 [26]. The monitoring system can run and record in real-time, independently from the
computer user interface, with the limitation of maintaining the last (or default) requested set point of temperature. The temperature inside the room was measured using PT100 temperature sensors which were connected to a data acquisition device (ALMEMO 710). The probes were calibrated for the range of temperatures of 0°C to 32°C, with a precision of 0.2÷0.5°C. Flir E6 IR camera was used which has a ±2% accuracy and a thermal sensitivity of <0.06 °C. A sketch with the location of the sensors is presented in Figure 2. They were placed at a height of approximately 1.5 m, on each wall (including floor, ceiling and diffuser). The PIV measurements were made with a classical system that has a dual pulsatory laser with a central unit, a command panel and a synchronizer, while the frames were captured with a CCD camera of 4 x 106 pixels resolution. The acquisition frequency of the PIV system was 7.5 Hz. The airflow was seeded from a fog generator. The image calibration gave a spatial resolution of 127 μm per pixel which is corresponding to a 300x300 mm² field of view. The assessment of the temperature fields was performed with the infrared camera using an extremely thin black cardboard which was placed in the median plane of the manikin. The grid of the cardboard has 50x50 mm (Length x Width).

2.2 Numerical

The numerical study was made in Ansys Fluent. The calculations were made using RANS method, in steady-state conditions. The turbulence model used was SST k-ω, with Pressure-Velocity coupling type Coupled and Least Squares Cell Based, Second Order or Second Order Upwind. The initialization was set to hybrid. Incompressible air was used as a fluid, with the gravity force activated. The convergence set for all residuals was 10⁻⁶. The temperature imposed on the walls in the OR was 24°C. The virtual manikins have a height of 1.75 m and a body surface of 1.8 m². A mesh independency study was made for the numerical model. The computational grids generated for this case have the following sizes: 5.1, 6.3, 6.5 and 7.5 million polyhedral elements. These computational grids resulted from cases with 16, 22, 24, and 28 million tetrahedral elements which were converted to polyhedral in Fluent. Different temperatures were used for the manikin, setting on their surface temperatures identical with the thermal manikins used during the experimental campaigns and similar with those of a healthy human subject (34°C – head, 32°C – core, 30°C – arms, 27°C – legs). The numerical studies that analyzed the airflow had the inlet for the fluid as the entire surface of the UAF, while the outlet was set as the entire surface of the corner diffusers (Figure 2). Figure 2 also presents the position and the dimensions of the local ventilation system, a mobile laminar air flow system (MLAF).

![Figure 2. Mesh sections with the interested domain around the manikin’s head](image)

Sections from the computational grid of the numerical case are presented in Figure 3 and 4. These pictures show mesh sections from the numerical case of 22 million tetrahedral elements, which was after converted in polyhedral, resulting a number of 6.3 million elements.
Figure 3. Mesh sections with the interested domain around the manikin’s head

Figure 4. Mesh sections with the interested domain: a) isometric view; b) sagittal plane

In these pictures it can be seen the difference in cell size using the option „body of influence”, the way of generating the boundary layer and the number of boundary layers. A maximum number of 8 boundary layers were generated. The growth rate was set at 1.1, while the layer height was generated in accordance with the cell size in the respective region.

3. Results

The comparations is highlighted in Figure 5 and 6. It can be observed that the temperature gradient has almost the same allure and the same height with the same gradient. Numerical velocity field results show some differences compared with experimental results mainly due to the shape of the manikin head and because we used pieces of black duct tape during the experimental session to prevent reflections from the laser beam. Due to this fact, a separation of the boundary layer emerged quicker in the left upper part of the head in the measurement campaign, resulting in a slightly different allure of the PIV velocity fields compared with the numerical results.

Figure 5. Temperature gradient around the manikin’s head: left – CFD, right – IR measurements

Airflow with a velocity of 0.3 m/s from the LAF diffuser and airflows from the MLAF diffuser in the range of 0.3÷0.7 m/s can be seen in Figure 8. In this study, the airflow from the MLAF was at an angle of 60°. The figures (Figure 8) show velocity vectors in the sagittal planes centred on the patient. In these figures it can be identified the peripheral recirculation at the LAF diffuser level and the recirculation behind the operating table. This type of study was repeated for velocities equal to 0.3, 0.5 and 0.6 m/s from the LAF. For all LAF cases (velocities between 0.3÷0.6 m/s), the airflow velocity from the MLAF have been maintained the same (between 0.3÷0.7 m/s). It has been noticed that an increased velocity from the diffusers have a greater increase the recirculation areas.
Also, another observation was that LAF diffuser velocities lower than 0.2 m/s, when LAF is placed at a height of 2.5 meters, cannot overcome the thermal plumes generated by the patient (Figure 7). Greater attention is needed for those cases where there is medical equipment with significant heat output.

**Figure 6.** Velocity vectors around the manikin’s head: left – PIV measurements, right – CFD
4. Discussions and conclusions

The purpose of the study was to analyze how a local ventilation system can influence the air distribution near the operating area, with the possibility to develop conclusions and / or technical solutions for reducing the number of germs in this area. It has been observed that for an OR with a LAF diffuser placed at a height of 2.5 meters, in the ceiling, it will be recommended to have velocities higher than 0.2 m/s, but paying attention that velocities of 0.5 m/s can affect the occupant’s thermal comfort. It was observed that a velocity higher with at least 0.1 m/s is needed for the airflow from the MLAF diffuser in order to overcome the disturbances of the airflow from the general LAF system. This allows the airflow from the MLAF diffuser to reach the operating area, if we consider the operating wound in the chest area. Of course, this observation is based on the configuration studied in this article. Another observation is related to the velocity’s values of 0.3 m/s from the MLAF diffuser which cannot reach the area of interest.
mainly because of the interaction with the airflow from the LAF diffuser. Thermal comfort issue should be addressed also in this case. It can be concluded that the optimal range of velocities resulting from this study would be 0.3÷0.5 m/s for the LAF diffuser and 0.4÷0.6 m/s for the MLAF diffuser.

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