CFD ANALYSIS OF A HIGH-TECH OPERATING ROOM USING STAR-CCM+®

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INTRODUCTION

A fully functioning high-tech Operating Room (OR) with a sophisticated ventilation system was built recently at the Technical University of Applied Sciences Amberg-Weiden in Germany, for teaching and research purposes. The high-tech OR enhances the university's Medical Engineering programs and acts as an innovation center for the regional health industry. The OR permits the exploration of a number of health-related R&D issues, including:

- Use and application of intraoperative imaging
- Technology integration
- Medical engineering planning
- Ergonomic concerns and use suitability
- Workflow and efficiency
- Hygiene and air conditioning / airflow technologies

With the recent surge in nosocomial infections (i.e. infections contracted in clinics or hospitals), finding new ways to effectively thwart contamination and ensure patient safety has become imperative [1].

Hygiene in medical environments, especially in the operating and procedure rooms, is of vital importance. In an implantation, joint or bone surgery for example, where large areas are exposed and must remain aseptic, there is a very high risk of nosocomial infection, and as such, maintaining a hygienic environment is a fundamental requirement. In order to eliminate the risk of contamination of the patient, OR staff or medical instruments, it is critical that the ingress of foreign particles or agents be reduced to a minimum.

In addition to inadequate hygiene, another risk factor concerns the disruption of airflow in an OR. Laminar AirFlows (LAF) are generated by special air conditioning systems in order to ensure a protective, germ-free air climate around the operating table. However, imaging procedures, OR monitors, or even ineffective OR lighting can adversely impact the protective effect of the laminar airflow. [2]

VENTILATION SYSTEM IN THE OPERATING ROOM

In accordance with the German hospital room Class 1 standard DIN 1946-4 ("Ventilation in Healthcare Buildings and Rooms"), the OR must have a Room Ventilation System (RVS) to regulate the inflow, filter the air and control the temperature and humidity in the room. The air goes through a grade H13 (absolute) High-Efficiency Particulate Air (HEPA) filter before being fed back into the OR. The

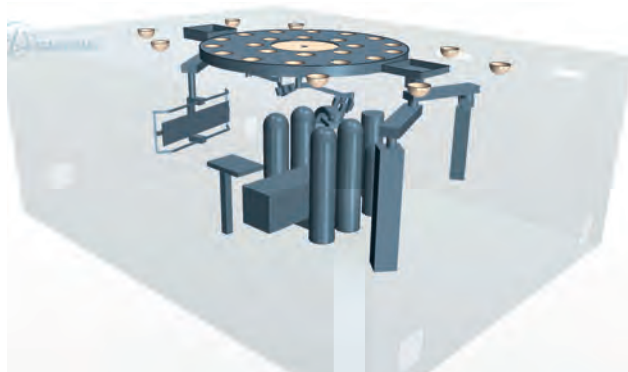


FIGURE 1: CAD model of the teaching and research OR

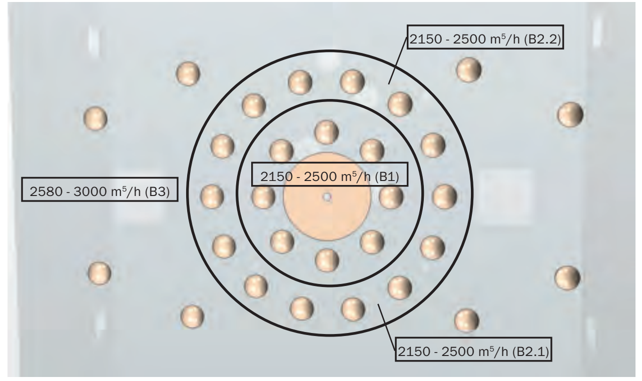
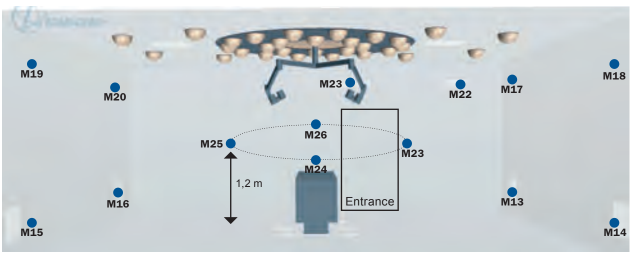


FIGURE 2: Simplified graphic representation of the air showers in the OR ceiling plane



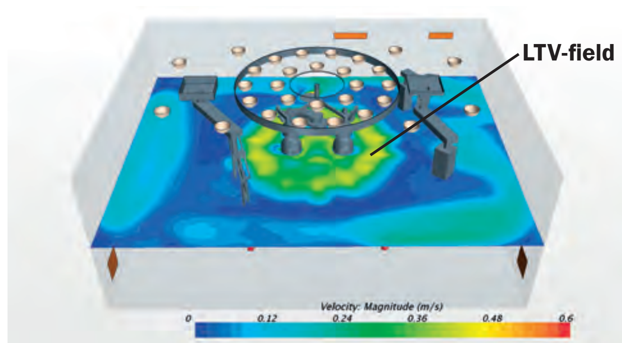


FIGURE 3 (ABOVE): Location of the measurement points in the OR
FIGURE 4 (RIGHT): Simulated air velocity in the area of the operating table (LTV = low-turbulence velocity)

filter, which is located in the ceiling panels directly over the operating and instrument tables, supplies a vertical LAF around the operating area in order to create a protective zone where exposure to germs is limited.

However, the laminar nature of the airflow, which is characterized by its slow and uniform velocity, is disrupted when it encounters lateral turbulence or obstructions such as OR lighting, OR staff, etc. on its way down [2].

A number of designs for the RVS system were considered. Eventually, the decision was made to use a conventional LAF 3200 mm x 3200 mm ceiling in conjunction with the new product Opragon®, developed by the Swedish firm Avidicare, in order to produce a Temperature-controlled Laminar AirFlow (TLAF).

AIRFLOW SIMULATION IN THE OPERATING ROOM

A number of CFD simulations were performed using STAR-CCM+ in order to analyze the airflow in the OR and assess the effectiveness of various ventilation techniques. After verifying the simulation's air velocities and temperatures against experimental data, the influence of OR imaging devices and other obstacles on the airflow was assessed.

As a starting point, a detailed CAD model of the OR was designed, including technical devices and personnel (see Figure 1). To this end, the geometry was simplified and unnecessary details which have little influence on the simulation results, such as grooves, edges and curves, were ignored. The entire ventilation system was simplified to include only inflow and outflow, and OR staff members were depicted as cylindrical dummies, which have dimensions in accordance with DIN 1946-4:2008-12. Windows, doors and the like were also ignored for this purpose.

As mentioned in the previous paragraph, the university's teaching and research OR adopted Opragon, a revolutionary technology developed by Avidicare, which supplies a TLAF in the OR. The filtered air flows through half-hemispheric-shaped openings ("air showers") into the OR. Two areas, corresponding to two different volumetric flow rates and temperatures are defined (see Figure 2): the Opragon (B1, B2.1 and B2.2), from where "cooled" HEPA-filtered air is blown onto the operating table and immediate surroundings, and the external area (B3), from where room-temperature HEPA-filtered air is emitted. The air emanating from the external air showers controls the room temperature while the air emanating from the Opragon (being 2 degree Kelvin cooler than the ambient air, and therefore of a higher density) "falls" directly down into the operative zone, forming in the process an ultra-clean air curtain.

VALIDATION OF STAR-CCM+ SIMULATION RESULTS AGAINST EXPERIMENTAL DATA

CFD simulations were performed using the k-epsilon turbulence model in STAR-CCM+.

Simulation Data	Deviation	Measurement Data
Air velocity LTV-field = 0,450 m/s	Δ Air velocity = 0,030 m/s (deviation of approximately 7%)	Air velocity LTV-field = 0,420 m/s

FIGURE 5: Comparison of simulated and measured air velocities

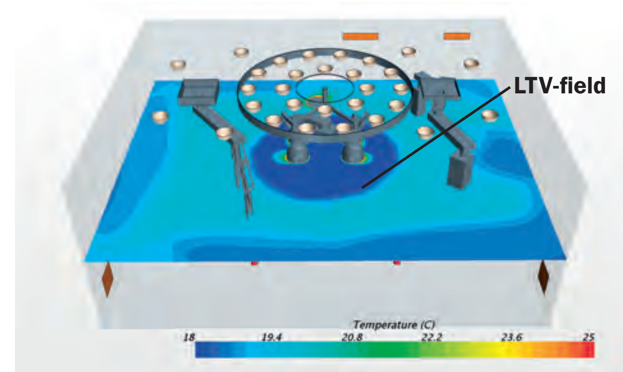


FIGURE 6: Temperature distribution in the area of the operating table (LTV = low-turbulence velocity)

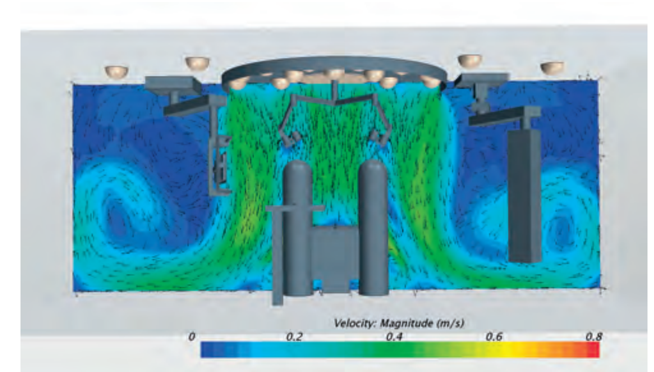


FIGURE 9: CFD simulation of a hybrid OR with temperature-controlled directional airflow

Simulation Data	Deviation	Measurement Data
Temperature LTV-field = 21,8°C	Δ Temperature = 0,4°C (deviation of approximately 2%)	Temperature LTV-field = 21,4°C

FIGURE 7: Comparison of simulated and measured temperature distributions

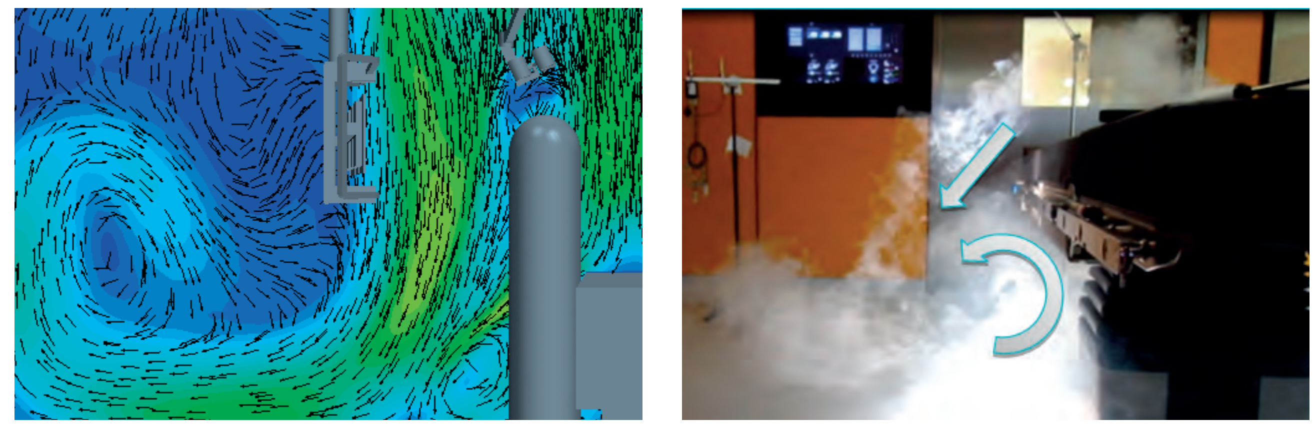


FIGURE 8: Comparison between simulated flow visualization (left) and smoke visualization test (right)

To verify and validate the CFD simulation, air velocity and temperature measurements in the teaching and research OR were conducted. Figure 3 shows the location of the points where the measurements were taken.

The difference between simulated ($V_{simulation}$ = 0.450 m/s) and measured air velocities ($V_{measurement}$ = 0.420 m/s) was found to be less than 7% (see Figures 4 and 5). The simulated values for the temperature distribution were also found to be in good agreement with the experimental data. A deviation of less than 2 % was achieved (see Figures 6 and 7).

The effect of the OR fixtures on the airflow was also assessed. Figure 8 shows the flow field in the vicinity of the operating table, where a recirculation zone was predicted. A smoke visualization test was also performed and confirmed this finding.

Through simulations, the observation was made that most medical devices (X-ray C-Bow, OR lighting, etc.), being located directly under the LAF ceiling, interrupt the protective TLAF flow, thereby posing an additional contamination risk. Additional turbulence zones introduced by airflow recirculation around the dummies ultimately cause impure air to flow from the outer area to the protected area, which increases the risk of microbiological contamination (see Figure 9).

CONCLUSION

Using CFD simulation, reliable predictions, both general and specific, about the airflow behavior and temperature distribution in the OR can be made. Furthermore, ventilation parameters can be optimized and general improvements suggested.

The CFD results presented here clearly show that the Opragon ventilation system is a step in the right direction. Nevertheless, they also indicate that ventilation technology in the OR can only function effectively if it is successfully combined with optimized medical devices/ fixtures and optimal work procedures.

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