Local and general ventilation system for an operating room with surgeons and patient

Laurentiu Tacutu^{1,2}, Ilinca Nastase^{1,2}, Florin Bode^{1,2,3}, Angel Dogeanu^{1,2}, Cristiana Croitoru^{1,2}

¹ CAMBI Research Center, Technical University of Civil Engineering Bucharest, 021414 Bucharest, Romania

² Technical University of Civil Engineering Bucharest, Faculty of Building Services, 021414 Bucharest, Romania

³ Technical University of Cluj-Napoca, Department of Mechanical Engineering, 400020 Cluj-Napoca, Romania

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 recommended by norms and guidelines. The research was approached by numerical and experimental studies. The thermal plume of the occupants (patient and surgeon) were measured by Particle Image Velocimetry (PIV) and thermography (IR). The results of the measurements were compared with the results from the numerical case. A mesh independence study was carried out for the numerical case. The study showed that velocities ≥ 0.2 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. For a long time, they have been classified as clean rooms, but their complexity tended to evolve along with the medical and technological field. The indoor environment quality of the ORs has 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 with either lateral or corner outlets. Another ventilation strategy that is often used is a mixed ventilation system with diffusers and the same configurations regarding the outlets. One common problem with the ventilation strategies in the ORs is the impossibility of the treated and filtered air to overcome the thermal plumes generated by the occupants and the medical equipment's [1, 2] and to reach the area of interest (operating wound) [3-5] in order to reduce the intra-operative infections, also called nosocomial infections [6-8]. 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 [9-11]. Besides these two problems, there is another topic of interest that refers to the large energy consumption of such ventilation systems [6, 12-14]. The high energy consumption is due to the high air changes per hour recommended in the existing norms worldwide. The general goal of this study is to determine how the air flow from a unidirectional air flow (UAF)[15] system, also

known as laminar air flow (LAF)[16] system, and a local ventilation system, similar to a mobile laminar air flow (MLAF)[17-20] 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.

2 Methods

The research was approached by numerical and experimental studies. The numerical model has been validated against experimental data. The experimental measurements were made in a climatic chamber which simulates a real scale OR. The OR geometry in the numerical simulations is identical with the climatic chamber where the measurements were made. The climatic chamber has an automation system for adjusting the wall temperatures and the ventilation system airflow. The ventilation system of the climatic chamber consists of a UAF with lateral outlets. In the numerical model was additionally added a MLAF ventilation system near the patient's head. In the measurements campaign we used a thermal manikin placed as a patient and another as a surgeon to simulate the natural heat release by convection, which is also known as thermal plume. The thermal manikins had different temperatures for each segment of the body (head, core, arms, legs), corresponding to a healthy human subject. The patient manikin was placed on an operating table and the surgeon manikin was placed near, under a UAF system, in both numerical and experimental studies. A mesh independence study was

* Corresponding author: ilincanastase@gmail.com

made for the numerical model. Particle Image Velocimetry (PIV) measurements were performed for determining the velocity profiles of the thermal plumes and infrared thermography measurements were made for determining the gradient temperature of the thermal plumes. The measurements and the simulations were made in isothermal conditions.

Fig. 1. Operating room geometry and the occupants

2.2 Experimental methodology

The experimental campaigns were made in isothermal conditions ($\approx 24^\circ\text{C}$), in a climatic chamber which simulates a real scale OR, that has a UAF ventilation system with lateral outlets and active controlled walls. The dimensions of the climatic chamber are 3.5x3.5x2.5m (Length x Width x Height). The temperature inside the cell was measured with 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 $0.2 \div 0.5^\circ\text{C}$. The employed IR camera was a FLIR E6, which has a $\pm 2\%$ accuracy and a thermal sensitivity of $< 0.06^\circ\text{C}$. 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 4×10^6 pixels resolution. The acquisition frequency of the PIV system was 7.5 Hz. The air flow was seeded with a fog generator. The image calibration gave a spatial resolution of μm per pixel which is corresponding to a $300 \times 300 \text{ mm}^2$ field of view. The temperatures of the thermal manikin were set to 34°C – head, 32°C – core, 30°C – arms, 27°C – legs. The time interval between two laser beams was set from $1000 \div 2000 \mu\text{s}$, capturing 500 images at a measurement. The thermal manikin used to simulate the patient is presented in detail in a previous article [21]. 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 that allowing to specify set-point values for each surface temperature of

the 79 zones, to monitor the evolution of temperature for a total of 395 available sensors, to record the electric power consumption of the segments and to assess the thermal sensation by using the equivalent temperature (t_{eq}) evaluation as presented in the standard EN ISO 14505/2 [22]. 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 other thermal manikin prototype used in this study as a surgeon has 36 individually controlled heating zones, monitor the evolution of temperature for a total of 144 available sensors [23]. It has also a dedicated software interface that allow the user to set and monitor the temperature values and power consumption on each zone. A sketch with the equipment used and their placement can be seen in Figure 2 (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).

Fig. 2. Sketch with the PIV measurement stand for: a) patient; b) surgeon

A sketch with the location of the sensors can be seen in Figure 3. They were placed at a height of approximately 1.5 m, on each wall (including floor, ceiling and plenum). 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 (Figure 4). The grid of the card board has 50×50

mm (Length x Width). Pictures from the PIV measurement campaigns can be seen in Figure 5.

Fig. 3. Sketch with the climatic cell and the placement of the temperature sensors

Fig. 4. IR measurements for gradient temperature: a) patient; b) surgeon

Fig. 5. PIV measurements for velocity vectors: a) patient; b) surgeon

2.2 Numerical methodology

The calculations were made using RANS method, in steady-state conditions. The turbulence model used was SST $k-\omega$, 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 m^2 . The meshes generated for this case have the following sizes: 6.8, 9.7, 13.6 and 13.9 million polyhedral elements. Different temperatures were used for the manikins, setting on their surface temperatures identical with the thermal manikins used in 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 thermal plume studies were made with no inlet and corner outlet, with hybrid initialization, although an initialization with a low velocity in the opposite direction of the gravity force has shown to help the calculation in the initial steps.

Fig. 6. The temperature conditions imposed for the numerical case

Initial studies to verify that the virtual manikins do not generate errors, due to unclosed surfaces or other similar things, were made (Figure 6).

Fig. 7. CFD velocity vectors, manikin tests: a) patient; b) surgeon

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 outlet corners (Figure 1). The UAF is centered on the surface of the ceiling, one part having the dimensions of $2500 \times 700\text{ mm}$ (Length x Width) and being two parts in total. The outlet is represented by diffusers placed in each of the 4 corners of the room, each corner having on small diffuser in the upper part and a larger diffuser in the lower part. The corner diffusers have the dimensions of $300 \times 250\text{ mm}$ and $500 \times 250\text{ mm}$ (Length x Width). The range of the velocities that were studied were between $0.3 \div 0.5\text{ m/s}$ for the UAF and $0.3 \div 0.7\text{ m/s}$ for the MLAF. The range of velocity used for the UAF represents the typical ranges of velocity recommended by the literature (norms, books, clean rooms good practice guidelines) [18-20, 24-26]. We didn't include in our analysis velocities lower than 0.3 m/s because it has been showed that for a typical height of 2.5 m for an OR, velocities $\leq 0.2\text{ m/s}$ may not overcome the thermal plumes from the occupants and the medical equipment [27-29]. The velocities used for the MLAF were obtained from the small number of articles that exists in this field. The velocities imposed on the surface of the MLAF were needed to be applied with an angle

(Table 1). Two air diffusion angles were selected to be analyzed for this study, 45° and 60°.

Table 1: Velocity components for MLAF system

Y comp = $v \cdot \sin(60^\circ)$	v [m/s]				
X comp = $v \cdot \cos(60^\circ)$	0.3	0.4	0.5	0.6	0.7
Y =	-0.28572	-0.38097	-0.47621	-0.57145	-0.66669
X =	-0.09144	-0.12192	-0.15241	-0.18289	-0.21337
Y comp = $v \cdot \sin(45^\circ)$	v [m/s]				
X comp = $v \cdot \cos(45^\circ)$	0.3	0.4	0.5	0.6	0.7
Y =	0.157597	0.210129	0.262661	0.315193	0.367725
X =	0.255271	0.340361	0.425452	0.510542	0.595632

The position of the MLAF and of the surgeons and patient can be seen in Figure 6.

Fig. 8. MLAF system position relative to occupants' position

The construction and the placement of the MLAF can be seen in Figure 8 and 9. The MLAF has 400x300 mm (Height x Width) and was placed at a 90 mm distance from the patient head. In these figures can be seen also the bend position of the surgeons over the patient, and the position of the hands of the patient which are also placed in a typical position for an OR scenario.

Fig. 9. MLAF diffuser dimensions and relative distance from the patient's head

Sections from the computational grid of a numerical case can be seen in Figure 10, 11 and 12. These pictures show mesh sections from the numerical case of 32 million tetrahedral elements, which was after converted in polyhedral, resulting a number of 9.7 million elements. 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 was 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.

Fig. 10. Front section of the computational grid of the OR, centered on the surgeons

Fig. 11. Sagittal section of the computational grid of the OR, centered on the surgeons

Fig. 12. Section of the computational grid with the head of a manikin

4 Results and discussions

A mesh independence study was made for the numerical case. Velocity vectors and temperature gradient comparisons were made between the numerical cases, from surgeon and patient. The comparisons can be seen in Figure 13÷16 and were made in a central axis, through an extraction of 200 points, on a height of about 600 mm. The data resulted was after the calculation was stabilized in the numerical model. For the surgeon, almost all the cases presented close results while for the patient the results revealed higher differences. The numerical model used was the one with 9.7 million polyhedral elements, which corresponded to the numerical case of 32 million tetrahedral elements. This model was chosen because no significant differences were found between the results

obtained from this model versus the results obtained from models with larger numbers of cells.

Fig. 13. CFD velocity vectors comparison for the surgeon

Fig. 14. CFD velocity vectors comparison for the patient

Fig. 15. CFD temperature gradient comparison for the surgeon

Fig. 16. CFD temperature gradient comparison for the patient

In order to validate the numerical case, comparisons between the results from the experimental and numerical case were made. These comparisons were made for velocity vectors and temperature gradients in central, sagittal planes. Figure 17 presents gradient temperature

from the two approaches for the surgeon. It can be observed that the temperature gradient has almost the same allure and the same temperature gradient on the same height.

Fig. 17. Temperature gradient for the surgeon: left – CFD; right – IR measurements

Surgeon velocity vectors from the two approaches can be seen in Figure 18. The velocity field captured by PIV measurements was composed from 3 different measurements sessions that were made for the front, the back and the upper part of the surgeon for a better resolution and due to the fact that some part of the measurement field was in the shadow of the manikin head. For the velocity fields comparisons, for both manikins, the numerical model reproduced better the forming of the boundary layer. Also, the head of the manikins from the numerical mode reproduced better the shape of the head. These details cannot be observed in the experimental study because the head of the manikin does not reproduce so faithfully a human head.

Fig. 18. Velocity vectors for the surgeon: left – PIV measurements; right – CFD

The values in the velocity field for the surgeon have the same ranges at the same height. A higher value of the velocity vectors in the back of the manikin can be seen in the numerical model and this is due to a better capture of the natural convective boundary layer that forms from the lower part of the manikin, which tends to grow in thickness and velocity. Results for the patient gradient temperature can be seen in Figure 19, while the velocity vectors from the patient can be seen Figure 20. Good correlation between the two approaches can be seen for the temperature gradient. For the velocity vectors, due to the shape of the head and the black duct tape used to prevent reflections from the laser beam, a break of the boundary layer was achieved in the left upper part of the head in the measurements, resulting in a slightly different allure of the PIV velocity fields.

Fig. 19. Temperature gradient for the patient: left – CFD; right – IR measurements

Fig. 20. Velocity vectors for the patient: left – PIV measurements; right – CFD

It can be seen (Figure 21) that for an angle of 45° of the airflow from the MLAF diffuser would not reach the area of interest, at most the patient's head. Thus, the numerical simulations for this angle were not continued.

Fig. 21. Velocity vectors in front planes, patient and surgeons, LAF 0.5 m/s, MLAF at 45°: a) 0.3; b) 0.6 [m/s]

Airflow with a velocity of 0.4 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 22 and 23. These figures show sagittal planes and frontal planes centered on one of the surgeon head. In these figures one can see the peripheral recirculation's at the LAF diffuser level, the recirculation's after the operating table or after other obstacles that are in the path of the airflow (surgeon head and hand). This type of study was also done for velocities from LAF 0.3, 0.5 and 0.6 m/s. The airflow from the MLAF velocities have been maintained the same, between 0.3÷0.7 m/s. It has been noticed that the higher the velocities from the diffusers, the greater the recirculation area after the obstacles. Also, another observation was that velocities lower than 0.2 m/s, or even 0.2 m/s in some cases, from a LAF diffuser that is placed at a height of 2.5 meters, cannot overcome the thermal plumes generated by the occupants. At the same time, increased attention should be paid to those cases where there is medical equipment with significant heat output.

Fig. 22. Velocity vectors in sagittal planes with only the patient, LAF 0.4 m/s, MLAF at 60°: a)0.3; b)0.4; c)0.5; d)0.6; e)0.7 [m/s]

Fig. 23. Velocity vectors in front planes, LAF 0.4 m/s, MLAF at 60°: a)0.3; b)0.4; c)0.5; d)0.6; e)0.7 [m/s]

5 Conclusions

The purpose of the study is 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 a 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 one step is needed for the airflow from the MLAF diffuser than the velocity of the airflow from the LAF (as example: 0.3 m/s LAF, 0.4 m/s MLAF). This allows the airflow from the MLAF diffuser to reach the operating wound, if we consider the operating wound in the chest area. Of course,

this observation is based on the configuration used in this case. Another observation regards the fact that velocities of 0.3 m/s of the airflow from the MLAF diffuser cannot reach the area of interest mainly because of the interaction with the airflow from the LAF diffuser. The same caution regarding the thermal comfort is valid here also. It can be concluded that the optimal range of velocities resulting from this study would be $0.3 \div 0.5$ m/s for the LAF diffuser and $0.4 \div 0.6$ m/s for the MLAF diffuser. Another important thing to consider is the obstacles that are placed in the path of the airflow (medical equipment, medical staff). Another observation was that the higher the velocity from the diffusers, the larger the recirculation zones were after the surgeon head and hand. The MLAF diffuser is the most likely solution to be implemented in the near future, that can work with a general ventilation system, in order to reduce intra-operative infections with germs, to reduce the high air changes per hour while maintaining the clean room demands, and to reduce the energy consumption. In order to implement this type of ventilation system, or others, more studies are needed to determine which is the efficiency of the system and how it is influenced by the different technical parameters (angles, dimensions, system / staff / wound position, other airflows in the room, and so on) and the scenarios commonly found in the ORs.

Acknowledgment

This work was supported by the grant of the Romanian National Authority for Scientific Research, CNCS, UEFISCDI, PHANTOM - Passive flow control for heat and mass transfer enhancement of impinging jets PN-III-P4-ID-PCE-2016-0758

Bibliography

- Yang C., Yang X., and Zhao B., *The ventilation needed to control thermal plume and particle dispersion from manikins in a unidirectional ventilated protective isolation room*. Building Simulation, 2015. **8**(5): p. 551-565.
- Dong, Z., et al., *Investigation of Thermal Plume around a Simulated Standing Operator in an Operating Room*. Procedia Engineering, 2017. **205**: p. 1940-1945.
- Cao, G., et al., *Do surgeons and surgical facilities disturb the clean air distribution close to a surgical patient in an orthopedic operating room with laminar airflow?* American Journal of Infection Control, 2018. **46**(10): p. 1115-1122.
- Memarzadeh, F., Manning, A., *Reducing risks of surgery*. ASHRAE Transactions, 2003. **45**(2): p. 28-33.
- James M, K.W., Nannaparaju MR, Bhamra JS, Morgan-Jones R., *Current evidence for the use of laminar flow in reducing infection rates in total joint arthroplasty*. The Open Orthopaedics Journal, 2015: p. 495-498.
- Memarzadeh, F. and W. Xu, *Role of air changes per hour (ACH) in possible transmission of airborne infections*. Building Simulation, 2012. **5**(1): p. 15-28.
- Thool, V.U., G.L. Bhooresddy, and B.J. Wadher, *Detection of resistance to linezolid in Staphylococcus aureus infecting orthopedic patients*. Indian J Pathol Microbiol, 2012. **55**(3): p. 361-4.
- Klevens, R.M., et al., *Estimating Health Care-Associated Infections and Deaths in U.S. Hospitals, 2002*. Public Health Reports, 2007. **122**(2): p. 160-166.
- Abreu, I., P. Ribeiro, and M.J. Abreu, *The issue of thermal comfort of medical clothing in the operating room*. DYNA, 2017. **84**(200): p. 234-239.
- Van Gaever, R., et al., *Thermal comfort of the surgical staff in the operating room*. Building and Environment, 2014. **81**: p. 37-41.
- Patania, F., et al., *Thermal comfort in operating rooms: a case study*. 2011. 105-114.
- Justo García-Sanz-Calcedo, Alfonso G. González, and David R. Salgado, *Assessment of Energy Consumption in Spanish Hospitals*. 2018: Springer, Cham.
- González, A.G., J. Sanz-Calcedo, and D. Rodríguez Salgado, *Evaluation of Energy Consumption in German Hospitals: Benchmarking in the Public Sector*. Vol. 11. 2018. 2279.
- English, T.R., *A simultaneous consideration of energy and ventilation in health care*. ASHRAE Transactions, 2014. **120**(2).
- Fischer, S., et al., *Reduction of Airborne Bacterial Burden in the OR by Installation of Unidirectional Displacement Airflow (UDF) Systems*. Medical Science Monitor : International Medical Journal of Experimental and Clinical Research, 2015. **21**: p. 2367-2374.
- Friberg, B., *Ultraclean laminar airflow operating rooms*. AORN Journal, 1998.
- JELLE LOOGMAN and I.D. VISSER, *A local ventilation system for the operating theatre*. REHVA Journal, 2015(August 2015).
- C. Pasquarella, G.E.S., S. Ferretti, E. Sacconi, M. Fanti, U. Moscato, G. Giannetti, S. Fornia, P. Cortellini, P. Vitali, C. Signorelli, *A mobile laminar airflow unit to reduce air bacterial contamination at surgical area in a conventionally ventilated operating theatre*. Journal of Hospital Infection, 2007: p. 313-319.
- D. Sossai, G.D., F. Sanguineti, F. Franchin, *Mobile laminar air flow screen for additional operating room ventilation: reduction of intraoperative bacterial contamination during total knee arthroplasty*. Journal of Orthopaedics and Traumatology, 2011: p. 207-211.
- Friberg, S., et al., *The addition of a mobile ultra-clean exponential laminar airflow screen to conventional operating room ventilation reduces bacterial contamination to operating box levels*. Vol. 55. 2003. 92-7.
- Dan, M.D., Paul; Ursu, Ioan; Nastase, Ilinca, *Advanced thermal manikin with neuro-fuzzy control **. Revista Romana de Inginerie Civila, 2017. **8**(4): p. 64-72.
- ISO, *Ergonomics of the thermal environment -Evaluation of thermal environments in vehicles Part 2: Determination of Equivalent Temperature*, in ISO 14505-2:2006. 2006, ISO.
- Nastase, I., C. Croitoru, and C. Lungu, *A Questioning of the Thermal Sensation Vote Index Based on Questionnaire Survey for Real Working Environments*. Energy Procedia, 2016. **85**: p. 366-374.
- ISO, *14644: Cleanrooms and associated controlled environments, in Part I*. 2015, ISO.
- ANSI, A., *Ventilation of Health Care Facilities*, in ANSI/ASHRAE/ASHE Standard 170. 2008.
- Normung, D.I.f., *Raumlufttechnik - Teil 4: Raumlufttechnische Anlagen in Gebäuden und Räumen des Gesundheitswesens in DIN 1946-4:2008-12*. 2008.
- Clark R.P. and Edholm O.G., *Man and his thermal environment*. 1985, London: E. Arnold.
- Tăcutu, L., et al., *Experimental and numerical investigation on the convective thermal plume around the head of the standing and lying human body*. E3S Web Conf., 2019. **85**: p. 02016.
- Tăcutu, L., et al., *Investigations on the convective thermal plume around the head of the standing and lying human body*, in *Indoor Air Conference 2018*. 2018/7: Philadelphia, PA, USA.