Numerical Analysis of Age of Air and Suspended Particle Distribution in Ventilated Operating Room

Riou Yamada [a], *Hideaki* Nagano [b], *Hidehiro* Asami [c], *U* Yanagi [d], *Shinsuke* Kato [e]

[a] Graduate School of Integrative Science and Engineering, Tokyo City University, Tokyo, Japan, g2181054@tcu.ac.jp

[b] School of Science and Engineering, Tokyo City University, Tokyo, Japan, hnagano@tcu.ac.jp

[c] School of Science and Engineering, Tokyo City University, Tokyo, Japan, g1812002@tcu.ac.jp

[d] School of Architecture, Kogakuin University, Tokyo, Japan, yanagi@cc.kogakuin.ac.jp,

[e] Office of Senior Professor, the University of Tokyo, Tokyo, Japan, kato@iis.u-tokyo.ac.jp

Abstract. This paper evaluates the indoor-air contamination caused by surgical smoke in the operating room and verifies the improvement caused by installing hanging walls suspended from the ceiling. A Computational Fluid Dynamics (CFD) analysis was performed to analyze the gas contaminant in the operating room with and without the installation of hanging walls suspended from the ceiling. The analysis showed how the downward air-conditioned flow blown from the ceiling surface and the upward flow caused by the hot surgical smoke interacted to form a complex flow field. Due to the close proximity of the source of smoke to the breathing zone, there was a steep gradient in the concentration of particles near the operating field.

Keywords. Operating room, Surgical smoke, Breathing air quality, CFD
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1. Introduction

In recent years, various electrosurgical tools, including laser scalpels and ultrasonic surgical generators are available for surgery. These tools work by burning biological tissue, creating large quantities of vapor and droplets in the air, especially when there is a lot of moisture. This is called surgical smoke, and its composition includes not only water vapor, but also substances harmful to medical staff and patients, including toxic gases such as benzene, toluene, and xylene, as well as bacteria and viruses [1-3]. In this case, the generation of contaminants in the operating room cannot be avoided. Therefore, to ensure breathing air quality, it is necessary to ensure that the contaminants that are generated are quickly exhausted before they reach the breathing zone of the medical staff.

Hence, the purpose of this study is to determine the diffusion characteristics of contaminants from surgical smoke by numerical analysis and to verify the effect of installing hanging walls to improve the quality of the air that is breathed by the medical staff.

2. Outline of simulation

A computational fluid dynamics simulation was conducted to evaluate the contaminant concentration distribution in the operating room and the effect of installing hanging walls to improve the simulated air chamber. The target space is an actual operation room with the highest level of cleanliness—class 100, based on US. Federal Standard 209 E—in the pulmonology ward of a university hospital in Shanghai, China [4-5]. The operation was a thoracotomy for the purpose of removing a tumor from the right lung of a patient. Table 1 shows the calculation conditions and Table 2 shows the boundary conditions. The computational model features an operating table in the center of the room with the air conditioning system blowing downward from the ceiling, just as in the actual operating room (Fig. 1). The analysis treated that all the particles were scalar transport and followed the airflow perfectly. The steady-state concentration distribution in space was analysed by solving the transport equation for the scalar quantity generated from the operating field at a constant rate. The simulated medical staff at the operating table were given an opening corresponding to the mouth, and their breathing was simulated by way of constant suction. Three heat sources were configured: the electrocautery used in the operating field, the human-generated metabolic heat, and the surgical light. To improve the quality of the air that is breathed by the medical staff, it is necessary for the air conditioned flow from the ceiling to reach the level of the breathing zone without diffusing. Therefore, several different hanging wall configurations

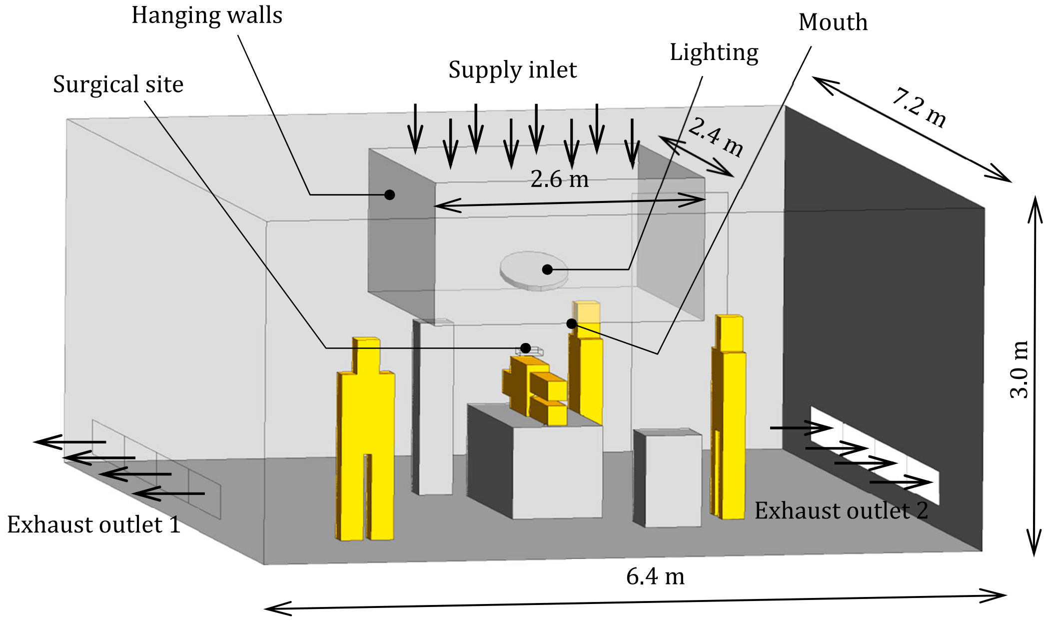

Fig.1 - Computational model of OR

Tab. 1 - Calculation condition.

Mesh type	Prism on human surface Tetra for space
Mesh number	3 million
Min. mesh height	5 mm
Governing equation	Continuity, RANS, Average heat transfer, Scalar transport
Time marching	Steady state
Turbulent model	SST *k*-*ω* model
Differential scheme	2nd order upwind
Pressure coupling	SIMPLE
Buoyancy	Incompressible ideal gas
Heat radiation	View factor

Tab. 2 - Calculation condition.

Inlet	Velocity	0.25 m/s
	(Air change rate	40 h^{-1})
	Turbulent intensity	5 %
	Turbulent viscosity ratio	10
	Temperature	21 °C
Outlet	Zero pressure	
Wall	No-slip / Adiabatic	
Respiration of medical staff	Continuous inhalation 0.71 m/s (14.4 L/min)	
Metabolic rate	86 W	
Electrocautery	300 W	
Surgical light	80 W	

Tab. 3 - Case condition.

	Case 1	Case 2	Case 3	Case 4
Height of hanging wall	N/A	1.25 m	0.25 m	1.25 m
Area of hanging wall region	N/A	2.6 x 2.4 m		0.88 x 0.8 m

were investigated to see if they would prevent the air conditioning airflow from mixing with the room air. The condition with no hanging wall was designated as Case 1. Cases 2 to 4 corresponded to the installation of pairs of hanging walls of different heights and enclosing different surface areas. The case conditions are shown in Table 3.

3. Results and discussion

3.1 Flow field

Fig. 2 shows the distribution of the flow velocity vectors. In all cases, the air conditioning airflow blown down from the ceiling vents is blocked by the surgical light and then diverted to the left and right exhaust outlets. In the upper corners of the room, vortices are formed where the flow velocity is low; hence, the air in that section is believed to remain in the same place for longer.

In the operating field, the surgical smoke generates an upward flow of heat with a velocity of about 0.30 m/s. Because the air conditioning airflow from the ceiling is blocked by the surgical light, an upward flow develops and is amplified by the metabolic heat generated by the medical staff. This, combined with the effect of inspiration by the medical staff, causes the surgical smoke to reach the level of the breathing zone, where it is inhaled by the medical staff. In Case 1, since there is no hanging wall, the air conditioning airflow is slowed by the shear stress caused by the velocity gradient with surrounding low-velocity airflow. However, in Case 2, which features hanging walls, the air conditioned flow appears to reach the bottom of the hanging walls without mixing or diffusing, allowing it to be delivered to the level of the breathing zone with its purity intact. Case 3 produces a similar effect, but because the hanging walls are shorter, the air mixes below it, and the improvement is not as significant. In Case 4, the hanging walls are

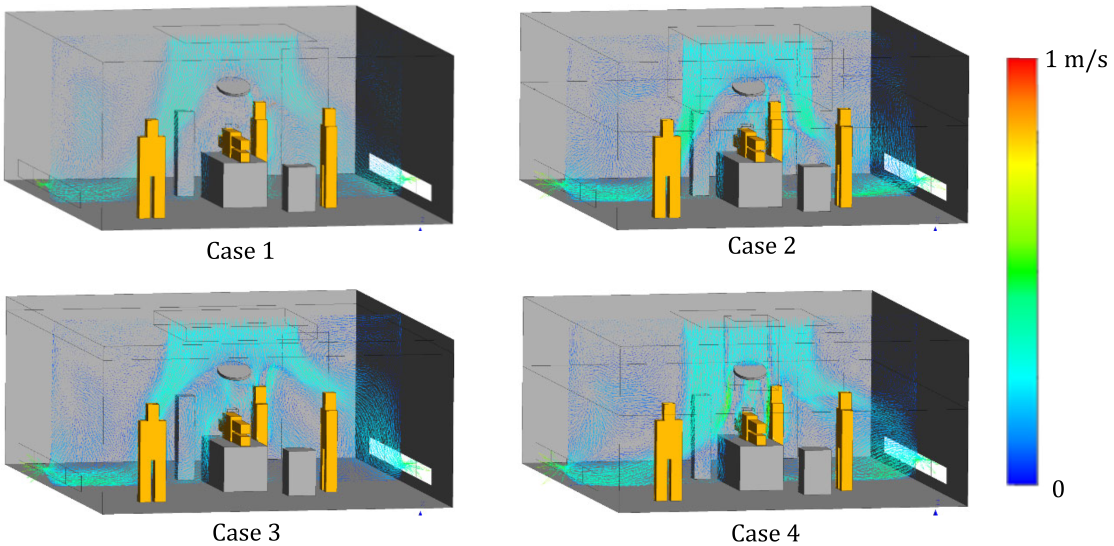

Fig. 2 - Airflow distribution

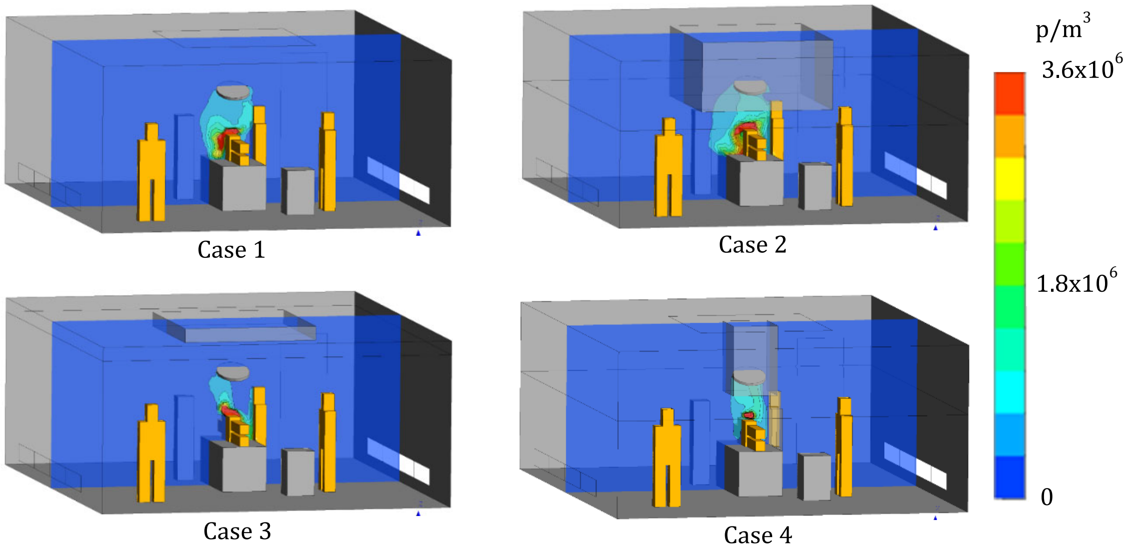

Fig. 3 - Concentration distribution

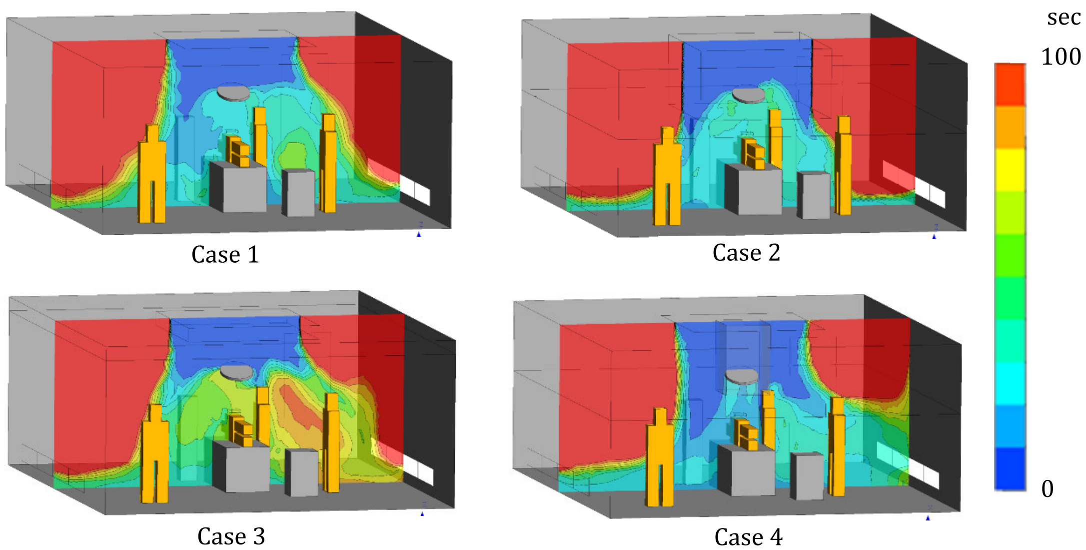

Fig. 4 – Age of air distribution

closer together, defining a narrower region with almost the same surface area as the surgical light. In this case, the air conditioning airflow passes both through and around the region defined by the hanging walls. This allows the air in the hanging wall area to reach the level of the breathing zone without any mixing at all.

3.2 Concentration distribution

Fig. 3 shows the concentration distribution. The numeric concentration levels (converted to number of particles) shown in the figure were calculated based on the measured number of particles at the outlets and the intensity computed in the CFD simulation [4-5]. In all four cases, the concentration gradient is steep in the vicinity of the breathing zone because the medical staff are positioned close to the source of the particles. In order to ensure the quality of the air in the breathing zone, it is important that the clean air blown from the ceiling reaches the breathing zone while remaining uncontaminated. In Case 4, however, the surgical smoke rises due to buoyancy, but the hanging walls prevent its diffusion. In the resulting flow field, the breathing zone is now directly downstream of the source of smoke; thus, the smoke ends up reaching the vicinity of the breathing zone.

3.3 Age of air distribution

The air age distribution is shown in Fig. 4. The figure shows that in all four cases, the blowout airflow from the ceiling has the youngest air age, with values of 10 seconds or less in the area between the ceiling and the surgical light. On the other hand, in the regions near the ceiling away from the air vents, areas of stagnation form with an air age of more than 100 seconds as the air stays in the place. The older age of the air in the operating field in the vicinity of the operating table is likely due to the complex flow field formed by the collision of the clean air blowing down from the ceiling against the upward flow of heat generated by the electrocautery and the human bodies. The upward flow entrains the ambient air from the floor and mixes it with the clean air, reducing its quality. In Case 3, the hanging walls allow the air to reach the breathing zone without mixing, which is an advantage. In Case 4, the effect of the hanging walls was even greater, and the air in the breathing zone was the youngest of all the cases. However, it is important to note that relatively younger air compared to other cases can still mean that the particle concentration is high if there is particle generation from a point source such as surgical smoke, as can be seen from the concentration distribution in the previous section.

4. Conclusions

This paper addressed the problem of contaminant generated by the use of electrocautery in the operating field. The contaminant concentration distribution was analysed by numerical analysis during surgery. It showed that the airflow from the ceiling was blocked by the surgical light, preventing clean air from reaching the operating field. The use of electrocautery produced an upward flow of heat that was amplified by the metabolic heat generated by the medical staff and affected the flow field in the breathing zone. Specifically, the breathing zone was characterized by steep gradient in the concentration of particles. The simulation also showed that the installation of hanging walls around the ceiling vent had a significant impact on the number of particles inhaled by the medical staff. Analysis of the distribution of the air age showed that under normal conditions without hanging walls, the blowout airflow is immediately mixed with the room air, but the installation of hanging walls was effective in suppressing the mixing and quickly bringing clean air to the operating field and the level of the breathing zone.

The pollutant source such as electrocautery analysed in this paper is in the vicinity of the breathing zone of the medical staff. In such a case, the fresh airflow through filtration from the air-conditioning system does not assure the breathing air quality. Not only the thermal plume caused by the electrocautery but also the surgical light prevent the downflow from reaching the breathing zone of the medical staff. The air-age distribution in the micro-environment around the surgical site needs to be analysed in order to locate the source on the upstream of the breathing zone.

5. References

[1] Centers for Disease Control and Prevention (Cdc), Health and Safety Practices Survey of Healthcare Workers, 2020. https://www.cdc.gov/niosh/topics/healthcarehsps/smoke.html. (Accessed 25 September 2021). accessed

[2] B.King, J. McCullough, Health Hazard Evaluation Report No. 2001-0066-3019 (CDC), 2006. https://www.cdc.gov/niosh/hhe/reports/pdfs/2001-0066-3019.pdf

[3] I.V. Limchantra, Y. Fong, K.A. Melstrom, Surgical smoke exposure in operating room personnel A review, JAMA Surgery 154 (No.10) (2019) 960-967, https://doi.org/10.1001/jamasurg.2019.2515

[4] Akane Odagiri, U Yanagi. The characteristic of particle spread in during open chest surgery in hospital operating room and the analysis of air flow, Roomvent 2020, ID277

[5] Akane Odagiri, U Yanagi, Shinsuke Kato, Comparison of Generation of Particles and Bacteria in Endoscopic Surgery and Thoracotomy. Building and Environment, 193 (2021) 107664. https://doi.org/10.1016/j.buildenv.2021.107664

Data Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.