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COMPUTATIONAL STUDY OF AN AIR VENTILATION SYSTEM BASED ON CFD SIMULATION IN HOSPITAL OPERATION THEATRE ENVIRONMENT

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By

MUNEERAH A B S FARAJ

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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By

MUNEERAH ABS FARAJ

April 2019

Chairperson : Kamarul Arifin Ahmad, PhD
Faculty : Engineering

In health-care facilities, pharmaceuticals, medical device production, laboratories, semiconductor production and the aerospace clean-room technology is widely implemented. The utility of the clean room allows for a range of benefits. The application is capable of reducing infection rates in health-care facilities. Hospital Operation Theatre (OT) are clean rooms which are equipped with sophisticated Heat Ventilation and Air Conditioning (HVAC) systems. HVAC system is functioned to provide Laminar Air Flow (LAF) for optimum cooling inside the OT, provide adequate number of Air Changes per Hour (ACH) and remove the air borne contamination from the surgical site. The main aim of the current work is to effectively test a HVAC system, which can provide adequate cooling with LAF and remove the contamination at the surgical site successfully. To archive the main aim, the CFD study need to validate with previous experimental work. Then parametric study need to be conduct to determine the optimal inlet and outlet configuration inside the OT. Next, the effect of heat load on the optimum airflow configuration need to be investigate using CFD software. Finally, the contamination particles need to be injected inside the optimum airflow configuration and track their movement. The parametric studies have considered various inlet and outlets along with the variation of their positions, thus effectively considering all the scenarios of Horizontal and Vertical LAF. From the result it can be concluded that vertical flow has superior efficiency compare to horizontal flow. Furthermore, the vertical flow has significant impact on the heat distribution inside the OT. Meanwhile, the horizontal flow has minimal impact on the heat distribution. Finally, the GENTRA accurately modeled the skin particles size density at various locations. The removal of the contaminants effectively from the OT shows the selected LAF for the OT works effectively in cooling the OT as well removes contamination. Increasing the contaminant particle size and density by two and three times also didn't affect the contamination removal, thus the inlet velocity and positive pressure in the OT was enough to carry the contaminants through the outlet vents.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KAJIAN KOMPUTASI SISTEM PENGUDARAAN BERDASARKAN SIMULASI CFD DI DALAM PERSEKITARAN DEWAN BEDAH HOSPITAL

Oleh

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Di kemudahan penjagaan kesihatan, farmaseutikal, pengeluaran peralatan perubatan, makmal, dan pengeluaran semikonduktor, teknologi bilik udara aeroangkasa telah digunakan secara meluas. Utiliti bilik bersih memberikan pelbagai faedah. Pengunaannya mampu mengurangkan kadar jangkitan di kemudahan penjagaan kesihatan. Dewan Bedah Hospital (OT) adalah bilik yang bersih yang dilengkapi dengan sistem Pengudaraan Haba dan Sistem Pendingin Udara (HVAC) yang canggih. Sistem HVAC berfungsi untuk menyediakan Aliran Udara Laminar (LAF) untuk penyejukan optimum di dalam OT, menyediakan jumlah Kitaran Udara per Jam (ACH) yang mencukupi dan mengeluarkan pencemaran udara dari tapak pembedahan. Matlamat utama penyelidikan adalah untuk menguji sistem HVAC, yang dapat memberikan penyejukan yang mencukupi dengan LAF dan membuang pencemaran di dewan pembedahan dengan jayanya. Untuk mengesahkan matlamat utama, kajian CFD perlu disahkan dengan penyelidikan sebelum ini. Kemudian kajian parametrik perlu dilakukan untuk menentukan konfigurasi masuk dan keluar yang optimum di dalam OT. Seterusnya, kesan beban haba pada konfigurasi aliran udara yang optimum perlu disiasat menggunakan perisian CFD. Akhir sekali, zarah-zarah pencemaran perlu dimasukan di dalam konfigurasi aliran udara yang optimum dan pergerakannya di analisa. Kajian parametrik telah mempertimbangkan pelbagai saluran masuk dan keluar bersama dengan variasi kedudukan mereka, dengan itu ia berkesan mempertimbangkan semua senario LAF iaitu mendatar dan menegak. Hasilnya dapat disimpulkan bahawa aliran menegak mempunyai lebih kecekapan berbanding dengan aliran mendatar. Selain itu, aliran menegak mempunyai kesan yang ketara ke atas pengedaran haba di dalam OT. Aliran melintang pula dilihat mempunyai kesan minimum terhadap pengagihan haba. Akhirnya, GENTRA dengan tepat memodelkan kepadatan saiz zarah kulit di pelbagai lokasi. Penyingkiran bahan cemar secara berkesan dari OT menunjukkan LAF yang dipilih untuk OT berfungsi dengan berkesan dalam penyejukan OT serta membuang pencemaran. Meningkatkan

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saiz zarah dan ketumpatan zarah oleh dua dan tiga kali juga tidak menjejaskan penyingkiran pencemaran, oleh itu halaju masuk dan tekanan positif di dalam OT cukup untuk membawa bahan cemar melalui saluran keluar.

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LIST OF ABBREVIATIONS

ACH	Air changes per hour
ANN	Artificial Neural Network
ASHRAE	American Society of Heating Refrigerating and Air-conditioning Engineers
BL	Boundary Layer
CFD	Computational Fluid Dynamics
DES	Direct Eddy Simulation
DNS	Direct Numerical Simulation
HEPA	High-Efficiency Particulate Air
HPC	High Performance Computing
HTM	Health Technical Memorandum
IAQ	Indoor Air Quality
LAF	Laminar Air Flow
LES	Large Eddy Simulation
ORs	Operating rooms
OT	Operation Theatre
PIV	Particle Image Velocimetry
RANS	Reynolds Averaged Navier Stokes
RNG	Re-Normalisation Group
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
SLE	Straight Leading Edge
SMA	Shape Memory Alloys
SPIV	Stereo Particle Image Velocimetry
SSI	Surgical Site Infection
SST	Shear Stress Transport
UCV	Ultra Clean Ventilation
UVGI	Ultraviolet Germicidal Irradiation

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LIST OF SYMBOLS

		units
2D	Two Dimensional	
3D	Three Dimensional	
G	Generation Term	N/m^3
K	Turbulent Kinetic Energy	m^2/s^2
KL	Laminar Kinetic Energy	
Re	Reynolds Number	
Re_θ	Transition Reynolds Number	
S	Source Term	N/m^3
δ	Boundary layer thickness	m
ε	Turbulence Dissipation Rate	m^2/s^3
ω	Specific Dissipation Rate	1/s

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CHAPTER 1

INTRODUCTION

Hospital consists of various departments such as OR, obstetrics, isolation, pathology, radiology, sterile service department etc., [1]. Each of these departments need specialised HVAC design to meet their specific requirements. HVAC in an OR is for the sole purpose of maintaining the Indoor Air Quality (IAQ) by minimizing infection and comfort of patient and staff [2, 3]. The design and maintenance of a clean operating room depends on the following factors, establishing the location of air intake, type of humidifier used, air cleaning, temperature and humidity inside the OR [4-7]. As per the recommended US department of health guidelines, the OR should have positive pressure and greater than 15 Air changes per hour ACH Sehulster et al., [8]. Lower and higher humidity levels affect the human comfort. Khalil [9] discussed the importance of effective HVAC design Figure 1, to obtain the required conditions inside OR to maintain the humidity for better IAQ. Khalil [10, 11].

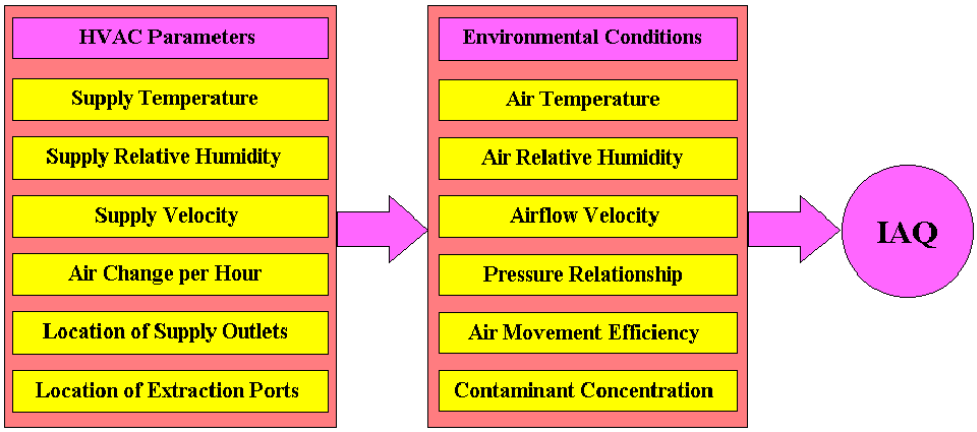

Figure 1.1: Parameters to maintain IAQ of OR [9]

The OR is equipped with large inlet and outlet vents for effective air changes. Air changes per hour (ACH) are carried out to reduce the effect of contaminants. A detailed guideline in designing of HVAC facility is provided in the, ASHRAE HVAC design manual for hospitals and clinics, [2] and ANSI/ASHRAE/ASHE Standard 170-2008 [12]. Figure 2 shows the ventilation system design of a typical OR. Lavy et al., [13] furthermore discussed the importance of designing energy efficient HVAC design. The energy requirement of hospitals in general is huge and in particular the OT, requirement is maximum compared to other areas [14-16]. The effect secondary infection due to transport of contaminants in the ventilation is system is discussed by [17- 29]. The effect of clothing on the thermal conditions of the surgical teams is reported in [30-34]. A brief review on the IAQ of OR's is discussed in [35- 41].

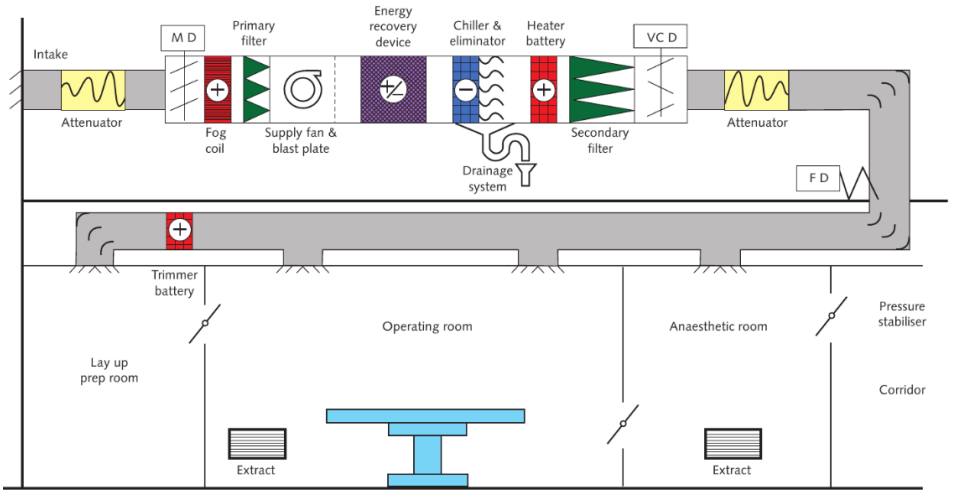

Figure 1.2: Typical OR ventilation system layout [1]

Two ventilation designs are considered 1. Cross flow 2. Impinging or vertical flow. The aim is to have Laminar Air Flow (LAF) to prevent the mixing of contaminants. The cross-flow system is one where in the diffuser is located on one wall and the exhaust vents are located on the other. In case of impinging or vertical flow, the diffuser is located on top of the operating table. Both the designs provide Ultra Clean Ventilation (UCV) as shown in Figure 3 and are equipped with High-Efficiency Particulate Air (HEPA) filters Dharan and Pittet [5]. In Plenum ventilation, the clean air is forced in columns from various overhead locations. Air quality has to be maintained in the OR's to reduce the infection to the patient and OR staff [42]. It has been a concern that blood borne pathogens from infected patients may affect the health of OR staff. The primary sources of bacteria are skin scales, facial hair, ears and clothing from the patient as well as the staff Owers et al., [9] and Drake [10]. Kamar and Kamsah [43] conducted experimental studies to measure the contamination inside the OR. Woloszyn et al., [44, 45] also conducted experimental and numerical tests to find the contamination distribution due to medical equipment and staff movement.

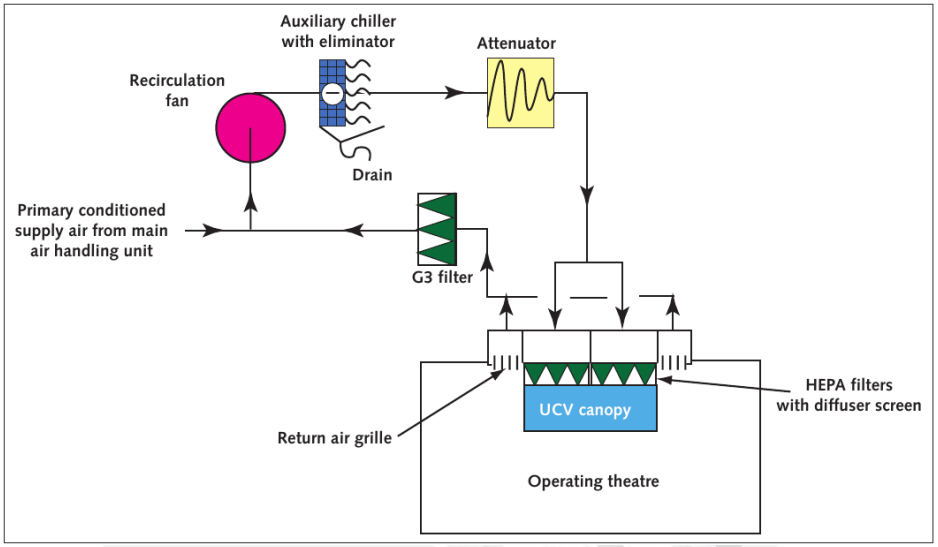

Figure 1.3: UCV Operation Theatre [1]

Study by Balaras et al., [31] considering 20 OR's in 10 hospitals in Greece with focus on the temperature, humidity and ventilation inside the OR, showed that the majority of the audited hospitals did not meet the health standard requirements. This shows the importance of HVAC auditing of hospitals is the need of the hour. An efficient design to control the airflow movement, in an operating room can be achieved through CFD. CFD studies in HVAC design are helping in energy efficient design by providing better solution for wall insulation, avoid leak in piping and duct system Huzayyin and Khalil [46] and Colquhoun and Partridge[47]. The four interrelated parameters which need to be considered for HVAC design in an OR are airflow, thermal comfort, contamination/aerosol control and heat dissipation. A review article by Chow and Yang [41] on the design of HVAC system for OR discusses the importance of LAF. Melhado et al., [35] conducted an in-depth review considering the effect of two different ventilation systems. 1. Conventional 2. LAF (cross flow and vertical), they also report of a combined system, where in LAF is combined with linear system to create two zones in an OR. They concluded that LAF ventilation was most effective in preventing the contamination. The above reviews are clearly showed that CFD application is currently needed in OR/OT research. The current review gives an in-depth insight into the studies implementing CFD in designing of OR

1.1 Problem Statement and Hypothesis

Surgical Site Infection (SSI) is mostly caused by the contamination inside the OT during an operation. It is associated with increased postoperative length of stay, increase costs, hospital re-admission rates and the use of antimicrobial agents. There are many aspects that could influence this type of infections: factors related to the patient, factor related to the surgical site and others related to the ventilation system of the OT environment. The main source of

contamination is the staff and patient, and the contaminant can be skin, hair or blood. The contamination on surgical site is an unavoidable reason for the occurrence of SSIs. Hence, the design an effective HVAC system is crucial to remove the contaminants from the OT environment.

Based on the previous work, CFD can simulate the movement of the contaminants inside the OT. This simulation can provide information about effectiveness of contaminants removal. Another important issue is thermal load inside the OT. This affects the movement of air as well as the IAQ. Other than that, the setup of the numerical method to simulate the contamination is also important. Most of the publications considered k-ε turbulence models, new low-transition Reynolds number turbulence models, such as Transition-SST and K-KL-ω may be more accurate Aftab et al., [104]. Beside the turbulence models, the setup of the contaminants inside the coding should be done accurately. The properties of the contaminants can be inserted into the codes.

In the current work, the author will focus on twofold. Firstly, the author will simulate and optimize the arrangement of the inlet and outlet of the air conditioning system. The purpose of this simulation is to check the effectiveness of the arrangement in removing the contaminants. Secondly, the author will optimize the best CFD setup for the proposed work.

1.2 Aims and Objectives

Hospital OT's are highly clean and exceptionally well-maintained rooms. The main issue in an OT is the Surgical Site Infection (SSI), which is the leading complication of implant or orthopaedic surgeries. The main aim of the current work is to effectively test a HVAC system, which can provide adequate cooling with LAF and remove the contamination at the surgical site successfully.

To achieve the above aim, four objectives must be achieved as described below

- To validate the CFD study with previous experimental work.
- To conduct a parametric study to determine the optimal inlet and outlet configuration inside an OT.
- To investigate the effect of heat load on the optimum airflow configuration using CFD.
- To inject contamination particles and track their movement inside the optimum airflow configuration.

1.3 Scope of work

The current work considers several important limitations. The first limitation is the design of the OT will be based on Kuwait requirement. Therefore, the size, number of people inside the OT, number of inlet and outlet will be following their standard. For example, the number of people inside the OT will be fixed to three

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people only where two are the hospital staff and one of them is the patient. Another example is the number of inlet and outlet will also be fixed with maximum of four inlet and eight outlets.

The second limitation is the general setup of the CFD simulation. The first setup is the flow will be treated as turbulence flow with maximum speed of 3 m/s. The second setup is the size of the contaminants is fixed at $1x10^{-5}$ m. The heat will come from two sources namely the lamp and the human body. The heat from the lamp is fixed at 300 W and the heat from human body is fixed at 100 W.

1.4 Thesis Organization

Chapter 1 introduces to the background of HVAC in hospital OT's. The thermal comfort, Indoor Air Quality (IAQ), and other aspects related to OT. It also highlights the motivation for the study, outlining the scope and objectives of the research.

Chapter 2 summarises the literature available on CFD studies related to hospital OT. A detailed in-depth review has been carried out in this chapter. The chapter deals with various studies incorporating CFD to study the different parameters inside the OT environment.

Chapter 3 deals with the numerical methodology used for conducting the validation study. It also includes the numerical methodology followed to carry out the parametric study.

Chapter 4 reports the numerical results. The validation and verification of the numerical results is reported. The results of the parametric study are also discussed.
Chapter 5 discusses the particle tracking mechanism implemented in the study. The results show the motion of various particles and their elimination from the OT.

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REFERENCES

[1] Department of Health, "Health technical memorandum 03-01: Specialised ventilation for healthcare premises. Part A. Validation and verification," *National Health Service, UK*, 2007.

[2] ASHRAE, "HVAC Design Manual for Hospitals and Clinics," *American Society of Heating, Air-Conditioning and Refrigeration Engineers, Inc., Atlanta, GA.*, 2013.

[3] A. Standard, "Standard 55-2004—Thermal Environmental Conditions for Human Occupancy," *ASHRAE Inc., Atlanta, GA*, 2004.

[4] V. R. Oviatt, "The Design and Maintenance of Operating Room Air Conditioning and Ventilating Systems (Engineering and Sanitation Section Report): Survey of Design Practices of Hospital Operating Room Air Conditioning and Ventilation System," *American Journal of Public Health and the Nations Health*, vol. 51, no. 12, p. 1902, 1961.

[5] S. Dharan and D. Pittet, "Environmental controls in operating theatres," *Journal of Hospital Infection*, vol. 51, no. 2, pp. 79–84, 2002.

[6] G. Cook and D. Int-Hout, "Air motion control in the hospital operating room," *ASHRAE Journal*, vol. 51, no. 3, p. 30, 2009.

[7] B. Drake, "Infection control in hospitals," *ASHRAE Journal*, vol. 48, no. 6, p. H12, 2006.

[8] L. Sehulster, R. Y. Chinn, M. Arduino, J. Carpenter, R. Donlan, D. Ashford, R. Besser, B. Fields, M. McNeil, and C. Whitney, "Guidelines for environmental infection control in health-care facilities," *Morbidity and mortality weekly report recommendations and reports RR*, vol. 52, no. 10, 2003.

[9] E. E. Khalil, "Thermal Comfort and Air Quality in Sustainable Climate Controlled Healthcare Applications," in *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 2010, p. 802.

[10] E. E. Khalil, "Tips on design of energy efficient hospitals air conditioning systems," in *ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2010, pp. 741–748.

[11] E. Khalil, "Energy Efficient HVAC Design Applications in Hospitals," in *2nd International Energy Conversion Engineering Conference*, 2004, p. 5591.

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[12] A. ASHRAE, “Standard 170-2008, Ventilation of Health Care Facilities,” *American Society of Heating, Air-Conditioning and Refrigeration Engineers, Inc., Atlanta, GA.*, 2008.

[13] S. Lavy, C. W. Kiss, and J. L. Fernandez-Solis, “Linking design and energy performance in US military hospitals,” *Architectural Engineering and Design Management*, vol. 11, no. 1, pp. 41–64, 2015.

[14] C. A. Short and S. Al-Maiyah, “Design strategy for low-energy ventilation and cooling of hospitals,” *Building Research \& Information*, vol. 37, no. 3, pp. 264–292, 2009.

[15] Z. A. Adamu, A. D. Price, and M. J. Cook, “Performance evaluation of natural ventilation strategies for hospital wards-A case study of Great Ormond Street Hospital,” *Building and Environment*, vol. 56, pp. 211–222, 2012.

[16] E. Essam and others, “Energy Efficient Hospitals Air Conditioning Systems,” *Open Journal of Energy Efficiency*, vol. 2012, pp. 1–7, 2012.

[17] E. G. Dascalaki, A. Lagoudi, C. A. Balaras, and A. G. Gaglia, “Air quality in hospital operating rooms,” *Building and Environment*, vol. 43, no. 11, pp. 1945–1952, 2008.

[18] E. S. Mousavi and K. R. Grosskopf, “Directional Airflow and Ventilation in Hospitals: A Case Study of Secondary Airborne Infection,” *Energy Procedia*, vol. 78, pp. 1201–1206, 2015.

[19] C. Pasquarella, P. Vitali, E. Saccani, P. Manotti, C. Boccuni, M. Ugolotti, C. Signorelli, F. Mariotti, G. E. Sansebastiano, and R. Albertini, “Microbial air monitoring in operating theatres: experience at the University Hospital of Parma.,” *J. Hosp. Infect.*, vol. 81, no. 1, pp. 50–7, 2012.

[20] W. Zoon, M. Loomans, and J. Hensen, “Testing the effectiveness of operating room ventilation with regard to removal of airborne bacteria,” *Building and Environment*, vol. 46, no. 12, pp. 2570–2577, 2011.

[21] A. Agodi, F. Auxilia, M. Barchitta, M. Cristina, D. D’Alessandro, I. Mura, M. Nobile, C. Pasquarella, I. S. G. of H. H. (GISIO, and others, “Operating theatre ventilation systems and microbial air contamination in total joint replacement surgery: results of the GISIO-ISChIA study,” *Journal of Hospital Infection*, vol. 90, no. 3, pp. 213–219, 2015.

[22] N. A. Al Laham, “Prevalence of bacterial contamination in general operating theaters in selected hospitals in the Gaza Strip, Palestine.,” *J Infect Public Health*, vol. 5, no. 1, pp. 43–51, 2012.

[23] J. Liu, H. Wang, and W. Wen, “Numerical simulation on a horizontal airflow for airborne particles control in hospital operating room,” *Building and Environment*, vol. 44, no. 11, pp. 2284–2289, 2009.

© COPYRIGHT UPM

[24] T. T. Chow and X. Y. Yang, “Ventilation performance in the operating theatre against airborne infection: numerical study on an ultra-clean system.,” *J. Hosp. Infect.*, vol. 59, no. 2, pp. 138–47, 2005.

[25] T. T. Chow, A. Kwan, Z. Lin, and W. Bai, “Conversion of operating theatre from positive to negative pressure environment.,” *J. Hosp. Infect.*, vol. 64, no. 4, pp. 371–8, 2006.

[26] H. Brohus, K. D. Balling, and D. Jeppesen, “Influence of movements on contaminant transport in an operating room.,” *Indoor Air*, vol. 16, no. 5, pp. 356–72, 2006.

[27] Y. Liu, A. Moser, and K. Harimoto, “Numerical study of airborne particle transport in an operating room,” *International Journal of Ventilation*, vol. 2, no. 2, pp. 103–110, 2003.

[28] C. Mendez, J. San José, J. Villafruela, and F. Castro, “Optimization of a hospital room by means of CFD for more efficient ventilation,” *Energy and Buildings*, vol. 40, no. 5, pp. 849–854, 2008.

[29] R. Kumar, R. Kumar, and A. Gupta, “Analysis of the ventilation system of an isolation room for a hospital,” *International Journal of Ventilation*, vol. 7, no. 2, pp. 139–149, 2008.

[30] M. Zwolińska and A. Bogdan, “Thermal sensations of surgeons during work in surgical gowns.,” *Int J Occup Saf Ergon*, vol. 19, no. 3, pp. 443–53, 2013.

[31] C. A. Balaras, E. Dascalaki, and A. Gaglia, “HVAC and indoor thermal conditions in hospital operating rooms,” *Energy and Buildings*, vol. 39, no. 4, pp. 454–470, 2007.

[32] R. J. Gordon, G. C. Bannister, K. E. Bowker, A. C. Mason, L. L. Cheung, and R. Eames, “Headwear in laminar flow operating theatres.,” *J. Hosp. Infect.*, vol. 73, no. 3, pp. 289–91, 2009.

[33] S. Mazzacane, C. Giaconia, S. Costanzo, and A. Cusumano, “A survey on the thermal conditions experienced by a surgical team,” *Indoor and Built Environment*, vol. 16, no. 2, pp. 99–109, 2007.

[34] J. Khodakarami and N. Nasrollahi, “Thermal comfort in hospitals-A literature review,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 4071–4077, 2012.

[35] M. A. Melhado, J. Hensen, and M. Loomans, “Review of ventilation systems in operating rooms in view of infection control,” in *Proceedings of the 6th Int. Postgraduate Research Conf.. in the Built and Human Environment, Technische Universiteit Delft*, 2006, pp. 478–487.

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[36] M. A. Melhado, M. Loomans, J. L. Hensen, and R. Lamberts, “Design of air distribution system in operating rooms-theory versus practice,” 2016.

[37] A. Abduladheem, K. Sahari, H. Hasini, W. Ahmed, and R. A. Mahdi, “Ventilation Air Distribution in Hospital Operating Room-Review,” *Int J Sci Res (IJSR)*, vol. 2, no. 11, 2013.

[38] L. Tacutu, I. Nastase, and T. Catalina, “A Critical Regard on Romanian Regulations Related to Indoor Environment Quality in Operating Rooms and a Technical Case Study,” *Energy Procedia*, vol. 85, pp. 511–520, 2016.

[39] B. M. Jones, M. J. Cook, S. D. Fitzgerald, and C. R. Iddon, “A review of ventilation opening area terminology,” *Energy and Buildings*, vol. 118, pp. 249–258, 2016.

[40] M. L. Pereira and A. Tribess, “A review of air distribution patterns in surgery rooms under infection control focus,” *Engenharia Térmica*, vol. 2, pp. 113–121, 2005.

[41] T.-T. Chow and X.-Y. Yang, “Ventilation performance in operating theatres against airborne infection: review of research activities and practical guidance,” *Journal of Hospital Infection*, vol. 56, no. 2, pp. 85–92, 2004.

[42] H. Humphreys and E. Taylor, “Operating theatre ventilation standards and the risk of postoperative infection,” *Journal of Hospital Infection*, vol. 50, no. 2, pp. 85–90, 2002.

[43] H. M. Kamar, N. Kamsah, W. K. Yinn, M. N. Musa, and M. S. Deris, “Fiedld Measurement of Airborne Particulate Matters Concentration in a Hospital’s Operating Room,” *Jurnal Teknologi*, vol. 77, no. 30, 2015.

[44] M. Woloszyn, J. Virgone, and S. Mélen, “Experimental study of an air distribution system for operating room applications,” *International Journal of Ventilation*, vol. 4, no. 1, pp. 1–11, 2005.

[45] M. Woloszyn, J. Virgone, and S. Mélen, “Diagonal air-distribution system for operating rooms: experiment and modeling,” *Building and Environment*, vol. 39, no. 10, pp. 1171–1178, 2004.

[46] O. Huzayyin and E. E. Khalil, “Flow Regimes and Thermal Patterns in Air Conditioned Operating Theaters,” in *9th AIAA/ASME Joint Thermophysics and Heat Transfer Conference*, 2005, vol. 3088, pp. 1–8.

[47] J. Colquhoun and L. Partridge, “Computational fluid dynamics applications in hospital ventilation design,” *Indoor and Built Environment*, vol. 12, no. 1–2, pp. 81–88, 2003.

© COPYRIGHT UPM

[48] T.-T. Chow and X.-Y. Yang, “Performance of ventilation system in a non-standard operating room,” *Building and environment*, vol. 38, no. 12, pp. 1401–1411, 2003.

[49] C. Buchanan and D. Dunn-Rankin, “Transport of surgically produced aerosols in an operating room,” *American Industrial Hygiene Association*, vol. 59, no. 6, pp. 393–402, 1998.

[50] M. N. El Gharbi, A. Benzaoui, E. E. Khalil, and R. Kameel, “Experimental and Numerical Investigations of Temperature and Relative Humidity in Different Surgical Operating Theatres,” in *7th International Energy Conversion Engineering Conference*, 2009, p. 4649.

[51] E. W. Ethbayah and E. E. Khalil, “Experimental and Computational Investigations of Thermal Patterns and Relative Humidity in Different Surgical Operating Theatres,” 2011.

[52] R. Kameel and E. E. Khalil, “Experimental and Numerical Investigations of Relative Humidity Characteristics in Hospitals,” in *43 rd AIAA Aerospace Sciences Meeting and Exhibit*, 2005, p. 2005.

[53] M. Farhad and J. Jiang, “Methodology for minimizing risk from airborne organisms in hospital isolation rooms,” 2000.

[54] F. Memarzadeh and A. P. Manning, “Comparison of operating room ventilation systems in the protection of the surgical site/Discussion,” *ASHRAE transactions*, vol. 108, p. 3, 2002.

[55] F. Memarzadeh and A. Manning, “Reducing risks of surgery,” *ASHRAE journal*, vol. 45, no. 2, p. 28, 2003.

[56] A. Eldegwy, E. E. Khalil, E. Bially, and S. Mourad, “Numerical Investigations of Indoor Air Quality in Infection Isolation Rooms,” in *13th International Energy Conversion Engineering Conference*, 2015, p. 3820.

[57] R. Kameel and E. E. Khalil, “Three-Dimensional Flow Regimes and Heat Transfer Characteristics in Surgical Operating Theatre,” *Journal of the Human-Enivronmental System*, vol. 5, no. 2, pp. 95–110, 2002.

[58] E. E. Khalil, “Numerical Computations of Air Flow Regimes in Healthcare Facilities and Their Experimental Verifications,” *IECEC Paper, AIAA-2009-4510*, 2009.

[59] R. Kameel and E. Khalil, “The prediction of airflow regimes in surgical operating theatres: a comparison of different turbulence models,” in *41st aerospace sciences meeting and exhibit, Reno, Nevada, AIAA-2003-0859*, 2003.

© COPYRIGHT UPM

[60] E. Khalil, “Mathematical Modeling of Fluid Flow Regimes Interactions in Complex Geometries,” in *41 st AIAA Aerospace Sciences Meeting \& Exhibit, Reno, NV*, 2003.

[61] R. Kameel and E. Khalil, *Energy efficient thermal comfort vs air quality in air-conditioned healthcare applications*. Eighth International IBPSA conference, 2003.

[62] E. E. Khalil, “Numerical Simulation of Flow Regimes and Heat Transfer Interactions in Complex Geometries,” *Proceedings, 5th IECEC, St. Louis, AIAA-2007-4726*, 2007.

[63] R. Kameel and E. E. Khalil, “Air flow regimes in operating theatres for energy efficient performance,” in *41st Aerospace Sciences Meeting, AIAA-2003-0686*, 2003.

[64] O. Huzzain and E. E. Khalil, “On the Modelling of Airflow Regimes in Surgical Operating Rooms,” in *43 rd AIAA Aerospace Sciences Meeting and Exhibit*, 2005, vol. 753, pp. 1–13.

[65] O. Huzayyin and E. Khalil, “Applications of Computational Techniques to Assess Energy Efficiency, Air Quality and Comfort in Air-Conditioned Spaces,” in *44th AIAA Aerospace Sciences Meeting and Exhibit*, 2006, vol. 1500, pp. 1–12.

[66] R. Kameel, E. Khalil, and N. Ramzy, “On In door Airflow Patterns Predictions Using CFD in Three Dimensional Configurations,” in *4th International Energy Conversion Engineering Conference and Exhibit (IECEC)*, 2006, p. 4095.

[67] E. E. Khalil, “Computer Simulation of Indoor Air Quality and Air Flow Regimes in Surgical Operating Theatres,” *Proceedings IAQVEC*, 2007.

[68] E. Khalil, “Flow Regimes and Thermal Pattern in Healthcare Facilities,” in *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2010, p. 6683.

[69] E. E. Khalil and K. Beshay, “Indoor Air Quality and Fuzziness Evaluation of the Airflow Distributions in Enclosures,” in *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, 2012, p. 1284.

[70] E. E. Khalil, F. A. C. I. T. WG, and I. T. WG, “Green Engineering in Clean Rooms and Surgical operating Theatres,” in *52nd Aerospace Sciences Meeting*, 2014, p. 1067.

[71] E. Khalil and G. ElHarriry, “Computer Aided Design of Air Flow Patterns, Energy and Air Quality in Healthcare Facilities Theatres,” in *46th AIAA Aerospace Sciences Meeting and Exhibit*, 2008, p. 1178.

© COPYRIGHT UPM

[72] E. E. Khalil, “Thermal Management in Healthcare Facilities: Computational Approach,” in *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition*, 2009, p. 1585.

[73] E. E. Khalil, “On the Modeling of Flow Regimes and Thermal Patterns Interactions in Complex Applications,” in *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 2010, p. 1554.

[74] E. E. Khalil and R. Kameel, “Experimental Investigation of Flow Regimes in An Operating Theatre of 1200-Beds Teaching Hospital,” in *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, 2010, p. 6933.

[75] C. Balocco, G. Petrone, and G. Cammarata, “Assessing the effects of sliding doors on an operating theatre climate,” in *Building Simulation*, 2012, vol. 5, no. 1, pp. 73–83.

[76] G. P. Lydon, D. B. Ingham, and M. M. Mourshed, “Ultra clean ventilation system performance relating to airborne infections in operating theatres using CFD modelling,” in *Building Simulation*, 2014, vol. 7, no. 3, pp. 277–287.

[77] E. B. Smith, I. J. Raphael, M. G. Maltenfort, S. Honsawek, K. Dolan, and E. A. Younkins, “The effect of laminar air flow and door openings on operating room contamination.,” *J Arthroplasty*, vol. 28, no. 9, pp. 1482–5, 2013.

[78] P. Kalliomäki, P. Saarinen, J. W. Tang, and H. Koskela, “Airflow patterns through single hinged and sliding doors in hospital isolation rooms-Effect of ventilation, flow differential and passage,” *Building and Environment*, vol. 107, pp. 154–168, 2016.

[79] M. Alsved, A. Civilis, P. Ekolind, A. Tammelin, A. E. Andersson, J. Jakobsson, T. Svensson, M. Ramstorp, S. Sadrizadeh, P.-A. Larsson, and others, “Temperature controlled airflow ventilation in operating rooms compared with laminar airflow and turbulent mixed airflow,” *Journal of Hospital Infection*, 2017.

[80] S. Dong, G. Tu, R. Cao, and Z. Yu, “Numerical study on effects of door-opening on airflow patterns and dynamic cross-contamination in an ISO class 5 operating room,” *Transactions of Tianjin University*, vol. 15, pp. 210–215, 2009.

[81] C. Balocco, G. Petrone, G. Cammarata, P. Vitali, R. Albertini, and C. Pasquarella, “Indoor Air Quality in a Real Operating Theatre under Effective Use Conditions,” *Journal of Biomedical Science and Engineering*, vol. 7, no. 11, p. 866, 2014.

© COPYRIGHT UPM

[82] R. Al-Waked, “Effect of Ventilation Strategies on Infection Control inside Operating Theatres,” *Engineering Applications of Computational Fluid Mechanics*, vol. 4, no. 1, pp. 1–16, 2010.

[83] C. Balocco, G. Petrone, and G. Cammarata, “Thermo-Fluid Dynamics analysis and air quality for different ventilation patterns in an operating theatre,” *International Journal of Heat and Technology*, vol. 33, no. 4, pp. 25–32, 2015.

[84] C. Balocco, G. Petrone, G. Cammarata, P. Vitali, R. Albertini, and C. Pasquarella, “Experimental and Numerical Investigation on Airflow and Climate in a Real Operating Theatre under Effective Use Conditions,” *International Journal of Ventilation*, vol. 13, no. 4, pp. 351–368, 2015.

[85] C.-C. Jung, P.-C. Wu, C.-H. Tseng, and H.-J. Su, “Indoor air quality varies with ventilation types and working areas in hospitals,” *Building and Environment*, vol. 85, pp. 190–195, 2015.

[86] J. McNeill, J. Hertzberg, and Z. J. Zhai, “Experimental investigation of operating room air distribution in a full-scale laboratory chamber using particle image velocimetry and flow visualization,” 2013.

[87] S. Sadrizadeh, A. Tammelin, P. Ekolind, and S. Holmberg, “Influence of staff number and internal constellation on surgical site infection in an operating room,” *Particuology*, vol. 13, pp. 42–51, 2014.

[88] S. Sadrizadeh, S. Holmberg, and A. Tammelin, “A numerical investigation of vertical and horizontal laminar airflow ventilation in an operating room,” *Building and Environment*, vol. 82, pp. 517–525, 2014.

[89] S. Sadrizadeh and S. Holmberg, “Effect of a portable ultra-clean exponential airflow unit on the particle distribution in an operating room,” *Particuology*, vol. 18, pp. 170–178, 2015.

[90] T.-T. Chow and J. Wang, “Dynamic simulation on impact of surgeon bending movement on bacteria-carrying particles distribution in operating theatre,” *Building and Environment*, vol. 57, pp. 68–80, 2012.

[91] S. Sadrizadeh, A. Afshari, T. Karimipanah, U. Håkansson, and P. V. Nielsen, “Numerical simulation of the impact of surgeon posture on airborne particle distribution in a turbulent mixing operating theatre,” *Building and Environment*, vol. 110, pp. 140–147, 2016.

[92] F. Romano, L. Marocco, J. Gustén, and C. M. Joppolo, “Numerical and experimental analysis of airborne particles control in an operating theater,” *Building and Environment*, vol. 89, pp. 369–379, 2015.

[93] Y. Yau and L. Ding, “A case study on the air distribution in an operating room at Sarawak General Hospital Heart Centre (SGHHC) in Malaysia,” *Indoor and Built Environment*, p. 1420326X13499359, 2013.

© COPYRIGHT UPM

[94] W. Zoon, M. van der Heijden, M. Loomans, and J. Hensen, “On the applicability of the laminar flow index when selecting surgical lighting,” *Building and Environment*, vol. 45, no. 9, pp. 1976–1983, 2010.

[95] A. Aganovic, G. Cao, L.-I. Stenstad, and J. G. Skogås, “Impact of surgical lights on the velocity distribution and airborne contamination level in an operating room with laminar airflow system,” *Building and Environment*, 2017.

[96] Z. J. Zhai and A. L. Osborne, “Simulation-based feasibility study of improved air conditioning systems for hospital operating room,” *Frontiers of Architectural Research*, vol. 2, no. 4, pp. 468–475, 2013.

[97] J. Abraham, B. Plourde, and L. Vallez, “Comprehensive review and study of the buoyant air flow within positive-pressure hospital operating rooms,” *Numerical Heat Transfer, Part A: Applications*, vol. 72, no. 1, pp. 1–20, 2017.

[98] F. Wang, J. Hung, Y. Chen, and C. Hsu, “Performance evaluation for operation rooms by numerical simulation and field measurement,” *International Journal of Ventilation*, vol. 16, no. 3, pp. 189–199, 2017.

[99] S. M. McHugh, A. D. K. Hill, and H. Humphreys, “Laminar airflow and the prevention of surgical site infection. More harm than good?,” *Surgeon*, 2014.

[100] J. Wang and T.-T. Chow, “Influence of human movement on the transport of airborne infectious particles in hospital,” *Journal of Building Performance Simulation*, vol. 8, no. 4, pp. 205–215, 2015.

[101] M. P. Bivolarova, A. K. Melikov, C. Mizutani, K. Kajiwara, and Z. D. Bolashikov, “Bed-integrated local exhaust ventilation system combined with local air cleaning for improved IAQ in hospital patient rooms,” *Building and Environment*, vol. 100, pp. 10–18, 2016.

[102] M. Loomans, I. de Visser, J. Loogman, and H. Kort, “Alternative ventilation system for operating theaters: Parameter study and full-scale assessment of the performance of a local ventilation system,” *Building and Environment*, vol. 102, pp. 26–38, 2016.

[103] O. Gofrit, C. Weissman, E. Peleg, N. Lifshits, R. Pinchover, and Y. Weiss, “Designing a modern surgical facility,” *Perioperative Care and Operating Room Management*, vol. 3, pp. 12–20, 2016.

[104] S. M. A. Aftab, A. S. M. Rafie, N. A. Razak, and K. A. Ahmad, “Turbulence Model Selection for Low Reynolds Number Flows,” *PloS one*, vol. 11, no. 4, p. e0153755, 2016.

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[105] F. Romano, L. Marocco, J. Gusten and C. M. Joppolo “Numerical and experimental analysis of airborne particles control in an operating theater,” *Building and Environment*, vol. 89, pp.369–379, 2015.

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Eng. Munerah A. Basheer Faraj has 2 years as a Contracting/ Service Engineer for Kuwait Oil Company and more than 6 years as contracting and maintenance manager for the Ministry of defense (MOD), hold a Master Degree in Mechanical Engineering from Coventry University, UK and a Bachelor Degree in Biomedical Engineering from Virginia Commonwealth University, USA. Master individual project, was on Using Solar Photovoltaic to provide Kuwait Armed Forces Hospital with Electricity. Bachelor senior design project was on pressure sensor used to measure pressure generated on opposing tissue surfaces during knot tying (for practice purposes for medical school students). She has published several journals in top ranking journals. She Conducted and arranged the First Armed Forces Biomedical Engineering Conference in Kuwait in December 2013. Participated in organizing various training courses along with the Kuwait association for biomedical engineers (KABME) in Kuwait society for engineers (KSE). She is a Board member in the KAMBE). A member in the IEEE Kuwait section, EMB Kuwait chapter, and Kuwait Society of engineers. Head of cultural committee with the national union of Kuwait students, USA, 2005-2007. Worked for the bio-track as an intern for the summer of 2008. The project was a blood coagulation analyzer produced by hemodyne.inc. The goals are to improve mechanical function and alignment, to fine tune data acquisition software, and to reduce electrical noise in signal.

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LIST OF PUBLICATIONS

Journals

F. Muneerah, S.M.A. Aftab and K.A. Ahmad "A Review on CFD Studies on HVAC in Operation Theatres", International Review of Mechanical Engineering (IREME), 2017. (Accepted for Publication)

F. Muneerah, S.M.A. Aftab and K.A. Ahmad, "Parametric Study to Determine Optimum HVAC in a Hospital Operation Theatre", Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, vol. 46, 2018. (Accepted for Publication)

F. Muneerah, S.M.A. Aftab and K.A. Ahmad, "Contaminant Tracking Using CFD in a Hospital Operation Theatre" Arabian Journal for Science and Engineering, 2018. (Under Review)

Conference Proceedings

F. Muneerah, S.M.A. Aftab and K.A. Ahmad "Parametric Study to Determine Optimum HVAC in a Hospital Operation Theatre", ICCMEH-2017, 19-20th December 2017 at Manipal Institute of Technology, Manipal, India.

F. Muneerah, S.M.A. Aftab and K.A. Ahmad "A Review on CFD Studies on HVAC in Operation Theatres", ICCMEH-2016, 17-18th December 2016 at Kyushu Institute of Technology, Kitakyushu, Japan.

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