Department of Mechanical & Chemical Engineering (MCE)
ISLAMIC UNIVERSITY OF TECHNOLOGY

IUT

Organisation of Islamic Cooperation

CFD analysis of Thermal Comfort & Contaminant removal from a typical Hospital Operation Theater

A thesis submitted to the Department of Mechanical & Chemical Engineering (MCE), Islamic University of Technology (IUT)

PREPARED BY:

Tousif Bin Alam (081446)

SUPERVISED BY:

DR. A. K. M. Sadrul Islam
Professor
Department of mechanical and chemical engineering
Islamic university of technology (IUT)
Board Bazar, Gazipur, Dhaka, Bangladesh

This thesis, as a part of partial fulfillment of Bachelor of Science in mechanical engineering degree, is submitted to Mechanical & Chemical Engineering Department of Islamic University of Technology (IUT), Gazipur, Dhaka, Bangladesh on October, 2012.

Department of Mechanical & Chemical Engineering (MCE)

ISLAMIC UNIVERSITY OF TECHNOLOGY (IUT)

October, 2012

DECLERATION OF CANDIDATES

This is to certify that this thesis or any part thereof has not been submitted anywhere else for the award of any degree or any publication

Signature of the candidate

____

Tousif Bin Alam

Student Number: 081446

Signature of the Supervisor

____

DR. A. K. M. Sadrul Islam

Professor
Department of mechanical and chemical engineering
Islamic university of technology (IUT)
Board Bazar, Gazipur, Dhaka, Bangladesh

ACKNOWLEDGEMENT

I express my heartiest gratefulness to almighty for his countless blessing, which enabled me to complete this thesis successfully. It is my pleasure to express sincere gratitude to my project supervisor **Prof. Dr. A. K. M. Sadrul Islam,** Department of Mechanical and Chemical Engineering, Islamic University of Technology (IUT) for his constant support, guidance, helpful suggestions and supervision at all stages of research work. The supervisor had dedicated his valuable time, even at odd hours, which ensured the completion of this project. I also express sincere gratefulness to **Prof. Dr. Md. Abdur Razzaq Akhanda,** Head of the Department**,** Mechanical and Chemical Engineering Department (MCE), IUT, for providing me all sort of support, special thanks go to our beloved parents whose love and inspiration kept us going during the project work.

I am also very much grateful to **Md. Hamidur Rahman,** Assistant Professor, Mechanical and Chemical engineering Department, IUT, who helped me a lot for learning the software ANSYS CFX.

I am highly indebted to the above mentioned persons and without their encouragement it would have been impossible to complete this dissertation.

Abstract

This Thesis paper presents CFD analysis of Thermal Comfort & Contaminant removal from a typical Hospital Operation Theater. This is a three dimensional analysis. The operation theater model includes a patient lying on an operating table, four surgical staff members standing around, and surgical lights above the patient. Cold clean air is supplied to the room through high sidewall grilles and exhausted through low sidewall grilles on the opposite wall. Steady state heat and mass transfer in the room are simulated by employing computational fluid dynamics modeling approach. Solutions of the distribution of airflow velocity, temperature, pressure, relative humidity, and contaminant concentration are presented and discussed. The predicted mean vote (PMV) is calculated for assessing thermal comfort of the occupants. The contaminant removal effectiveness (CRE) and the mean contaminant concentration in the breathing zone are used to assess the ventilation performance of the room. Effects of horizontal locations of supply and exhaust grilles on thermal comfort and contaminant removal are explored. Regression models for thermal comfort and contaminant removal as functions of these locations are built for design optimization. It is found that an overall better performance can be achieved by placing the supply grilles closer to the vertical centerline of the wall while the location of the exhaust grilles is somewhat insignificant.

Table of Content

Chapter 1

Introduction

1.1 Overview of The thesis

The entire health care unit, chemical industry, manufacturing industry, different machine shops & much commercial occupancy require ventilation and air conditioning for thermal comfort as well as for the removal of contaminants and other pollutions. A good design of ventilation & air conditioning system gives a very comfortable & healthy environment for the patients, people & also for doctors & staffs. Poorly ventilated workspaces not only make people feel uncomfortable but also may make them infected or intoxicated since the likelihood of air borne pathogens or other kinds of toxic chemicals is quite high. The thermal comfort and contaminant removal is very important for an operation theater. Pure and contaminant free air is very much important for a patient. During the time of operation, many contaminants also come out from patient's body. In an operation theater, many chemical components, medicine may use, which are harmful for both patient and the surgical staffs. Not only that, if we do not ensure thermal comfort in the operation theater, then it may effect on the body of the patients. Many chemical and medicine use in the surgery, may not keep well over a certain temperature. Some anaerobic virus and bacteria may attack at the higher temperature.

For these reason, thermal comfort and contaminant removal is very much important for a typical hospital theater. By using modern technology, it is easier to remove all the contaminant and make a thermal comfort environment throughout the room. But for a country like Bangladesh, it is very difficult to set up such a costly equipment to remove the contaminant and maintain thermal comfort. That is why the ventilation system is very important for our country. If we can design the ventilation system, so that we can remove the contaminant without any external equipment and achieve most thermal comfort, then it would be most economical for us.

By using ANSYS CFX simulation, we achieved the most desirable room design. We can achieve maximum thermal comfort and maximum contaminant removal by changing the position of the ventilation system.

1.2 A Typical Operation theater

An operating theater was a non-sterile, tiered theater or amphitheater in which students and other spectators could watch surgeons perform surgery. Within the Commonwealth nations, the term is used synonymously with operating room (OR) or operating suite, the modern facility within a hospital where surgical operations are carried out in a sterile environment.

Contemporary operating rooms are devoid of a theater setting (though some in teaching hospitals may have small galleries), making the term "operating theater" a misnomer for the modern facility. Operating rooms are spacious, easy to clean, and well-lit, typically with overhead surgical lights, and may have viewing screens and monitors. Operating rooms are generally windowless and feature controlled temperature and humidity. Special air handlers filter the air and maintain a slightly elevated pressure. Electricity support has backup systems in case of a black-out. Rooms are supplied with wall suction, oxygen, and possibly other, anesthetic gases. Key equipment consists of the operating table and the anesthesia cart. In addition, there are tables to set up instruments.

1.3 Thermal Comfort

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. Maintaining this standard of thermal comfort for occupants of buildings or other enclosures is one of the important goals of HVAC (heating, ventilation, and air conditioning) design engineers.

Thermal comfort is affected by heat conduction, convection, radiation, and evaporative heat loss. Thermal comfort is maintained when the heat generated by human metabolism is allowed to dissipate, thus maintaining thermal equilibrium with the surroundings. It has been long recognized that the sensation of feeling hot or cold is not just dependent on air temperature alone. Thermal comfort calculations according to ANSI/ASHRAE Standard 55

1.4 Contaminant Removal

Contaminant removal or Disinfection is a process used to reduce the number of pathogenic microbes (biological contamination) in air. It is required by the Air Treatment Rule for all systems that obtain their purity of air in the room and as well as in the whole environment. Disinfection is a process used to reduce the number of pathogenic microbes (biological contamination) in air.

1.5 Simple solution to get Thermal Comfort

In most buildings, air circulates through channels called ducts. Ducts are generally made of lightweight metal and may use other material for connections and insulation. These can be within walls or outwardly visible. Frequently, they are above ceilings or in crawl spaces. It is important for property owners to inspect ducts regularly, including upon first installation and after 10 years of use. Improper conditions in ducts can lead to energy loss and higher energy costs.

➢ Duct quality and connections

A quick inspection of ducts can often identify holes and bad connections. On average, 20% of transmitted air is lost as a result of improper duct work. Mastic sealant and metal tape are simple solutions for these issues. Some supply ducts may benefit from insulation, depending on external temperatures and intermediate spaces.

➢ Cleaning ducts and vents

Ducts and vents should be cleaned internally. Many ducts can be cleaned with long-hosed vacuums. Others many require removal and reinstallation. Vents should be cleared of any obstructions, including furniture. Faulty, blocked or unclean ducts or vents can prevent air flow and create temperature backups, causing more maintenance problems and raising energy costs for unconnected rooms. Rooms are most efficient when they have both input and output vents; in other words, supply air and return air.

Windows and doors

Windows and doors are an essential part of the heating system and should be sealed carefully into their surrounding spaces. They can also be chosen for their insulation values. Windows should be positioned and treated to maximize winter light and keep out summer light. Simultaneously, correct window usage can decrease summer cooling costs. Where windows have to be opened during cold months for ventilation or cooling, the building's heating and ventilation systems need to be addressed. Direct outside air is difficult to filter and will affect indoor air quality.

Programmable thermostats

Programmable thermostats are an easy way to maximize heating and cooling efficiency. These have internal timers which can be set to activate during certain hours of the day and even certain days of the week. Offices spaces which are unoccupied on nights or weekends can greatly benefit from these settings. Installing automatic thermostats reduces labor costs and reduces reliance upon individual tenant activity.

1.6 Simple Solutions to Reduce Indoor Air Pollution

We cannot stress the importance of reducing, and/or removing the source of the indoor air pollution. This may be a contaminated carpet, wall, or even ventilation (HVAC) system.

Ensure proper ventilation

Once the sources to pollution have been removed, the air must be cleaned and circulated with natural outdoor air. Increase the amount of outdoor, natural air coming indoors. Open windows, doors, turn on fans in windows, attics, crawl spaces, and turn on kitchen and bathroom exhaust fans, and air conditioning units with vent open.

Ensure proper air filtration/cleaning

The EPA provides a comprehensive list of air cleaners ranging from small table-top versions to sophisticated whole-house models.

- **Replace Old Filters**

Old filters in heating, air conditioning, and ventilation units (HVAC), can be a major cause of indoor air pollution, and must be monitored, and replaced if necessary.

- **Reduce and Remove Moisture**

The simple fact is that mold needs moisture to live. Control moisture and control mold.

1.7 Patient Safety Alert

This Patient Safety Alert alerts healthcare organizations to the release of a World Health Organization (WHO) Surgical Safety Checklist for use in any operating theatre environment. It is a tool for the relevant clinical teams to improve the safety of surgery by reducing deaths and complications.

1.8 HVAC System Design

HVAC (heating, ventilation, and air conditioning) is the technology of indoor and automotive environmental comfort. HVAC system design is a major sub discipline of mechanical engineering, based on the principles of thermodynamics, fluid mechanics, and transfer. The design of a heating, ventilating, and air-conditioning (HVAC) system for an operation theater is aimed to prevent the risk of infections during surgical operations while maintaining an adequate comfort condition for the patient and the surgical staff. Proper indoor comfort condition and indoor air quality are prerequisites for securing a safe and suitable environment for an operating room.

1.9 ASHRAE Standard for Room Condition

ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers), founded in 1894, is a building technology society with more than 50,000 members worldwide. The Society and its members focus on building systems, energy efficiency, indoor air quality, refrigeration and sustainability within the industry. The ASHRAE Handbook is a four-volume resource for HVAC&R technology and is available in both print and electronic versions. The volumes are Fundamentals, HVAC Applications, HVAC Systems and Equipment, and Refrigeration. One of the four volumes is updated each year.

ASHRAE also publishes a well recognized series of standards and guidelines relating to HVAC systems and issues. These standards are often referenced in building codes, and are considered useful standards for use by consulting engineers, mechanical contractors, architects, and government agencies. These are legally unenforceable, except when referenced as mandatory provisions in building codes, but are commonly accepted standards for architects and engineers.

There are standards to guide the design of air-conditioning systems for operating rooms around the world among which the American Institute of Architects has guidelines for design and construction of hospitals and health care facilities in the USA. From HVAC design point of view, ASHRAE Applications Handbook recommends general guidelines for an operating room that temperature should be kept in the range of 68–76°F (20–24°C), relativity humidity should be kept between 50% and 60%, positive air pressure should be maintained, and all air exhausted with no recirculation is preferred.

Chapter 2

Literature Review

Literature Review

A number of experimental studies have been presented about infections and related factors in operating rooms. Woods et al. presented a study to identify and demonstrate control strategies that could reduce energy requirements while not producing harmful effects on the environmental quality within the operating room. It was done through extensive literature search, development of mathematical and biophysical models, and analysis of data obtained in two existing operating rooms with different system performance characteristics. A trend toward less settling of viable particles was observed in the circulated air system. It was also found that thermal control for the comfort of the occupants might affect the sepsis control within the microenvironment. Lewis studied the influence of room air distribution on the infection rate in an operating room and concluded that an optimal air distribution plays an important role in maintaining the proper environmental condition within a surgical room. Conventional operating room HVAC distribution systems may be entirely satisfactory when properly designed, balanced, and maintained if postoperative infection is not a significant problem. More effective air distribution will be justified where the infection problem has more severe consequences or results in a higher cost of treatment. Memarzadeh proposed a methodology for minimizing contamination risk from airborne organisms in hospital isolation rooms. The results show that the number of particles deposited on surfaces and vented out is greater in magnitude than the number killed by ultraviolet (UV) light, suggesting that ventilation plays an important role in controlling the contaminant level.

Memarzadeh and Manning presented an extensive study on operating room ventilation systems and their effect on the protection of the surgical site, focusing on preventing the risk of postoperative infection from many factors including patient factors, surgical field factors, room factors, and HVAC factors. Mora et al. studied thermal comfort in operating rooms. The thermal environment was studied in two operating rooms in a hospital.

Thermal comfort was estimate based on the model proposed by Fanger in addition to questionnaires. It was concluded that the only means to provide thermal comfort for the surgical staff was to eliminate or to minimize the heat transfer from the surgical lights. They suggested that more research is needed to evaluate an acceptable thermal environment in operating rooms.

It can be observed that there is a need to predict ambient conditions within an operating room. Balaras et al. presented an overview of general design for acceptable indoor conditions related to HVAC systems in hospital operating rooms. Audits of 20 operating rooms in 10 hospitals were recorded covering a wide range of information on construction, ownership, type and condition of HVAC and auxiliary systems. Data on the assessment of the indoor conditions from 560 medical personnel working in-situ were also collected based on personnel questionnaires. Kameel and Khalil proposed guidance to architectural and mechanical engineering designers to optimize the comfort and hygiene conditions in operating theatres. Later, Khalil and Kameel studied the balance between thermal comfort and air quality in healthcare facilities to optimize the indoor air quality (IAQ) from the viewpoint of the air-conditioning design. They introduced recommendations for airside designs to facilitate the development of optimum HVAC systems in healthcare applications.

Chapter 3

Computational Fluid Dynamics

3.1 CFD Analysis

Computational fluid dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved. Ongoing research yields software that improves the accuracy and speed of complex simulation scenarios such as transonic or turbulent flows.

3.2 Recent CFD works on HVAC systems

CFD in recent years have opened the possibilities of low-cost yet effective method for improving HVAC systems in the design phase, with fewer experiments required. Memarzadeh and Manning studied the performance of a ventilation system in a typical patient room using CFD modeling.. Hirnikel et al. investigated contaminant removal effectiveness (CRE) of three air distribution systems for a bar/restaurant by using CFD modeling. The CRE was considered for both particulate and carbon monoxide dispersions, which represented the modeled environmental tobacco smoke (ETS), at two different ventilation rates. The results showed that directional airflow systems can reduce people's exposure to contaminants. Memarzadeh and Manning simulated contaminant deposition in an operating room using CFD air flow modeling and showed that a laminar flow condition is the best choice for a ventilation system when contaminant deposition is considered. The contaminant considered in this simulation study is a particle-type square, or skin scale, around 10 lm in size, released from three locations in the room and tracked to determine if they would impinge on either the surgical site or a back table.

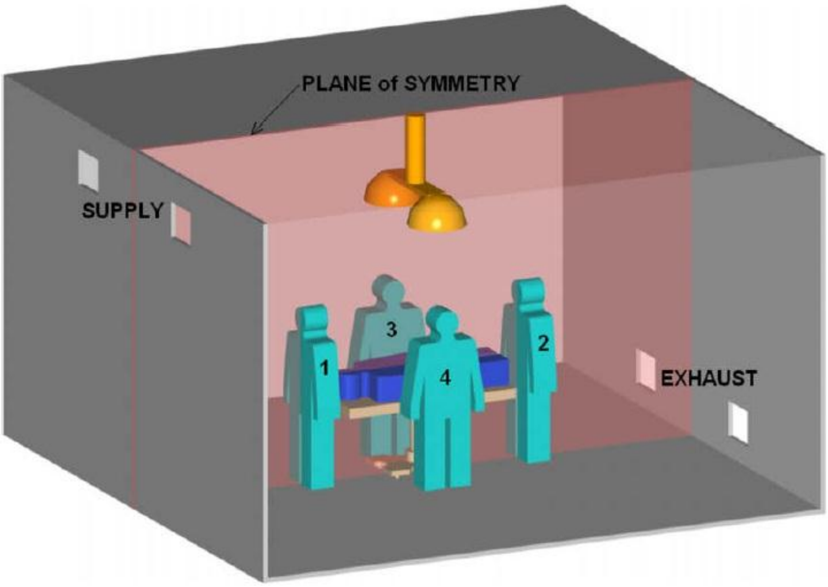
Kameel presented the use of a three-dimensional time-dependent CFD model to assess the airflow characteristics in different air-conditioned spaces. It was found that the extraction port location is a critical design factor and has a direct effect on heat removal efficiency and the energy efficiency of air-conditioning systems.

Chow and Yang used CFD analysis to simulate the temperature distribution, airflow pattern, and contaminant dispersion supported by observations and field measurements in a case study and concluded that the application of CFD is useful to help understand the adequacy of the ventilation design in renovation planning to match up-to-date engineering standards.
Jayaraman et al. reported a CFD study of containment of airborne hazardous materials in a ventilated room containing a downdraft table with the consideration of a range of ventilation configurations. Helmis et al. presented an experimental and theoretical study on assessing the status of air quality in a dentistry clinic with respect to chemical pollutants and identifying the indoor sources associated with dental activities.

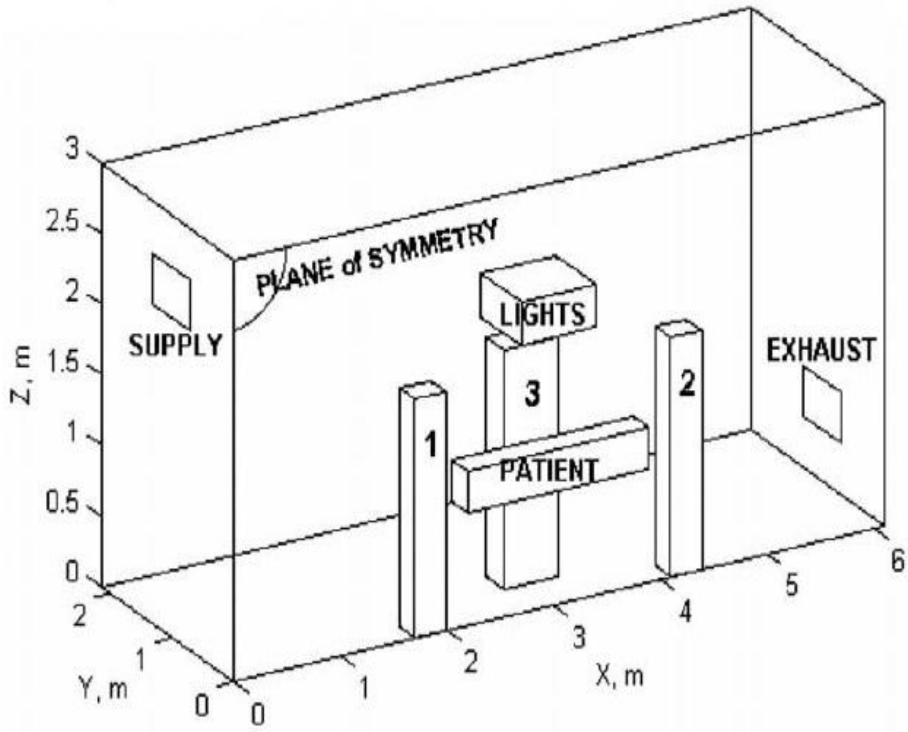
Different schemes of natural ventilation were explored to examine their effects on the indoor comfort conditions for the occupants in terms of air renewal. Rui et al. studied the airborne transmission of bacteria in two operating rooms during two surgeries: a surgical stitching of fractured mandible and a joint replacement surgery. Field measurements and numerical simulations were carried out. The results showed that improving airflow pattern could reduce particle deposition on critical surfaces.

3.3 My simulation Aim

The present work aims to study both thermal comfort and contaminant removal in a hospital operation theater. CFD modeling approach is used to find the numerical solution for the fluid flow and heat and mass (water vapor and contaminant gas) transfer inside the Operation Theater. Fig. 1a shows the basic setup for an operation theater including a patient lying on an operating table with a surgical staff of four members standing around under a set of surgical lights. Fresh cold air is supplied to the room through supply grilles at high position on the front (left) wall to remove the heat loads from the lights and from the bodies of people, and to remove contaminant if there is any. The exhaust grilles are located at low heights on the opposite (right) wall as the basic setup. Full-scale three-dimensional model is built for a finite-element based numerical solution of the problem. Reynolds decomposition, also known as Reynolds Averaged Navier–Stokes equations (RANS) approach is used to model the turbulent flow. The distribution of air velocity, temperature, relative humidity and contaminant concentration are found and examined to explore the related transport phenomena. Mean contaminant concentration in the breathing zone and CRE are calculated to assess ventilation performance of the room. Predicted mean vote (PMV) model is used to assess the personal thermal comfort conditions of the occupants (the patient and the surgical staff). Nine CFD simulations with various combinations of the locations of the supply and exhaust grilles are done to relate the influence of these locations on thermal comfort and contaminant removal.



(a) Basic Arrangement



(b) Computational Model

Fig. 1. Model of an operation Theater

Chapter 4

Mathematical model

Mathematical Model

To assess thermal comfort and contaminant removal, air velocity, temperature, and water vapor and contaminant concentrations need to be determined. These can be found by solving the system of coupled governing equations for the conservation of mass (for the whole air mixture as well as for each species), momentum, and energy. Steady-state incompressible flow of air as a multi component fluid, which includes dry air, water vapor, and a contaminant gas, is considered. The fluid properties are taken as constants except the varying density for buoyancy term in the momentum equation. The equation for the conservation of mass applied to the air mixture as the carrying fluid is given by

$$\nabla . u = 0 \qquad (1)$$

The buoyancy force term arising from density variation is included by means of the Boussinesq approximation based on the assumptions that the variation of fluid density affects only the buoyancy term and the fluid density is a function of temperature only. The equation for the conservation of linear momentum is given by

$$\rho u . \nabla u = - \nabla p + \mu \nabla^2 u + \rho g \beta (T - T_{ref}) \qquad (2)$$

Assuming that there is no heat generation, thermal conductivity is scalar, energy fluxes due to inter-diffusion and Dufour effect are negligible, and the equation for the conservation of energy is given by

$$\rho c_p u. \nabla T = k \nabla^2 T \qquad (3)$$

Assuming that the mass diffusivities of species in the airflow are scalars, thermal diffusion is negligible, and there is neither source nor chemical reaction, the equations for the mass conservation of water vapor and contaminant gas as carried species are given by

$$u. \nabla \omega_w = D_{w/a} \nabla^2 \omega_w \qquad (4)$$

$$u. \nabla \omega_c = D_{c/a} \nabla^2 \omega_c \qquad (5)$$

In order to take into account the turbulent effects, the RANS approach with a mixing length turbulent viscosity model is applied to the governing Equation (1) – (5). To define the problem completely, appropriate boundary conditions are required at each boundary segment of the computational domain. For the momentum Eq. (2) and continuity Eq. (1), boundary conditions are applied as follows: prescribed velocity on the supply opening, and zero velocity on solid surfaces (walls, people's bodies, etc.). For the energy Eq. (3), constant temperature condition is applied on the supply opening and people's body surfaces, constant heat flux on the heated surfaces of the surgical lights, and thermally insulated (no heat flux) on the walls, floor and ceiling. For the specific Equation (4) And (5), constant concentration of water vapor and zero concentration of contaminant are applied on the supply opening, constant flux of water vapor on people's body surfaces, constant flux of contaminant releasing from the patient, and zero mass flux on other solid surfaces.

The solution obtained by solving the system of governing Equation (1)– (5) With associated boundary conditions gives the distribution of seven primary variables, namely, three velocity components, pressure, temperature, water vapor concentration, and contaminant concentration. Based on these primary variables, relative humidity and PMV can be found. From the values of temperature, water vapor concentration, and pressure, relative humidity can be computed by using the procedure recommended in ASHRAE Fundamentals Handbook as follows:

$$\Phi = p_w/p_{ws} \qquad (6)$$

Where

$$P_w = (101325+p)*\omega_w/(0.62198 + 0.37802\ \omega_w) \qquad (7)$$

PMV is a parameter for assessing thermal comfort in an occupied zone based on the conditions of temperature and humidity along with metabolic rate, clothing, and air speed. PMV values refer to the ASHRAE thermal sensation scale that ranges from _3 to 3 as follows: 3 = hot, 2 = warm, 1 = slightly warm, 0 = neutral, _1 = slightly cool, _2 = cool, _3 = cold. According to ANSI/ASHRAE Standard 55-2004, the acceptable thermal environment for general comfort is recommended as _0.5 < PMV < 0.5.

To assess the effectiveness of the ventilation system of an occupied zone, the CRE can be used. The CRE factor involves the values of mean contaminant concentration at the supply and exhaust openings and in the breathing zone as

$$\mathbf{CRE = (C_E - C_S) /(C_{BZ} - C_S)} \qquad \mathbf{(8)}$$

The ‘‘breathing zone” is defined in ANSI/ASHRAE Standard 62.1- 2004 as ‘‘the region within an occupied space between planes 3 and 72 in. (75 and 1800 mm) above the floor and more than 2 ft (600 mm) from the walls or fixed air-conditioning equipment.” A similar concept is the ‘‘occupied zone” defined in ANSI/ASHRAE Standard 55-2004 as ‘‘the region normally occupied by people within a space, generally considered to be between the floor and 1.8 m (6 ft) above the floor and more than 1.0 m (3.3 ft) from outside walls/windows or fixed heating, ventilating, or air-conditioning equipment and 0.3 m (1 ft) from internal walls.” For the present problem, the ‘‘breathing zone” can be considered the same as the ‘‘occupied zone” and the ‘‘sterile zone”.

Chapter 5

CFX Simulation

5.1 Basic Simulation Process

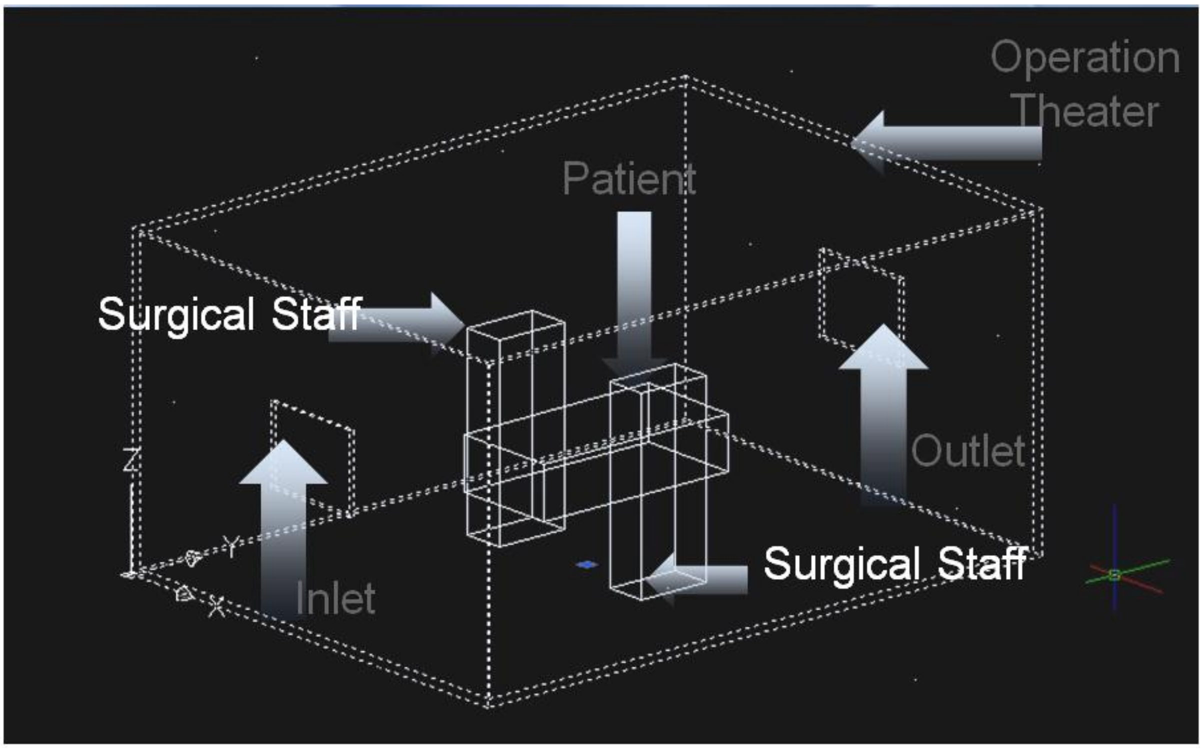
CFD modeling approach is used to find the numerical solution for the fluid flow and heat and mass (water vapor and contaminant gas) transfer inside the operation theater. The basic setup for an operation theater including a patient lying on an operating table with a surgical staff of four members standing around with a surgical light. The patient, the staffs & the light are identified with the rectangular shape box for the simplification of drawing. Fresh cold air is supplied through supply grilles at high position on the front (left) wall. The exhaust grilles are located on the opposite (right) wall as the basic setup. During the time of CFD simulation, we have to change the position of Supply & Exhaust horizontally. For different horizontal location we will get different results. The efficient design has to find out from the experiment. From the literature review; it is found that an overall better performance can be achieved by

- placing the supply grilles closer to the vertical centerline of the wall
- Location of the exhaust grilles is somewhat insignificant.

5.2 Simulation Flow

- ✓ First of all we have to simulate the system by meshing the geometry in the ANSYS CFX
- ✓ This time we just consider only a patient & two staffs without heat source
- ✓ Completing the design of the Operation Theater

The operation theater design is already made by using the AutoCAD software which is shown in the next.



AUTOCAD Design of a typical operation theater

5.3 Geometry Input in ANSYS & Meshing

The geometry completed in the AutoCAD has to mesh in the ANSYS CFD. After finishing meshing, we have to put the geometry in the CFX Pre to define the inlet, outlet & the boundary has to define to run the simulation work.

The process is shown in the next.

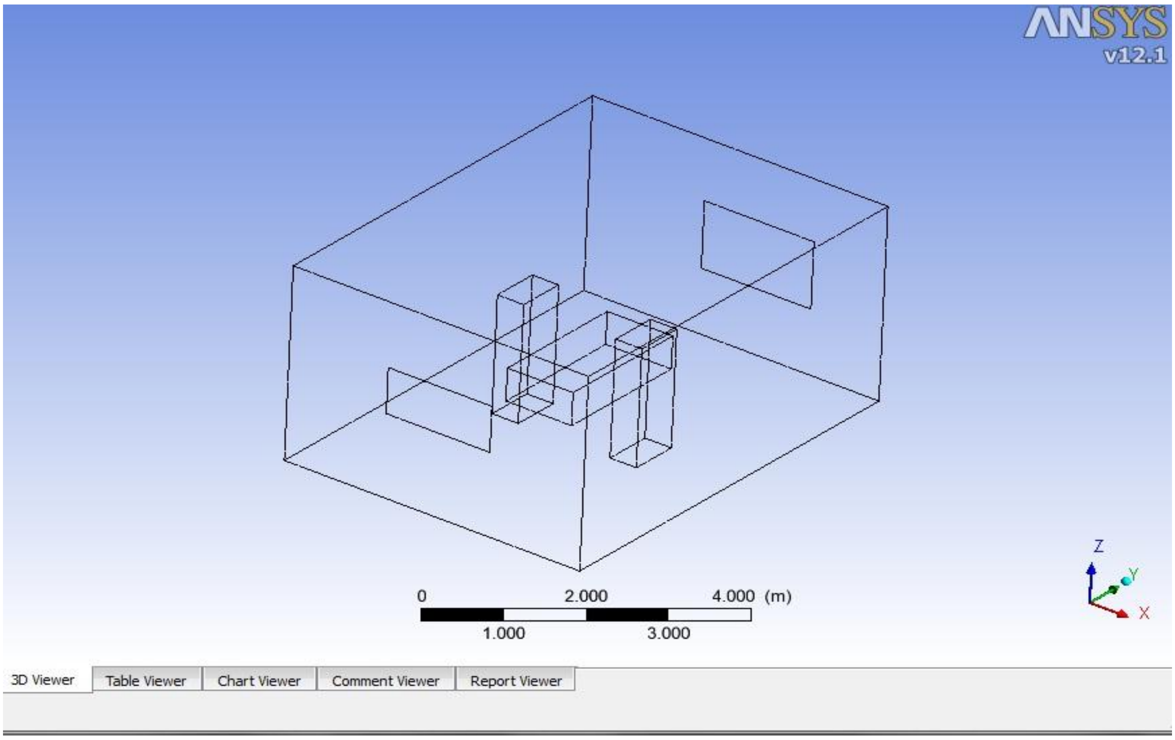


Fig. 2(a) Geometry input in ANSYS

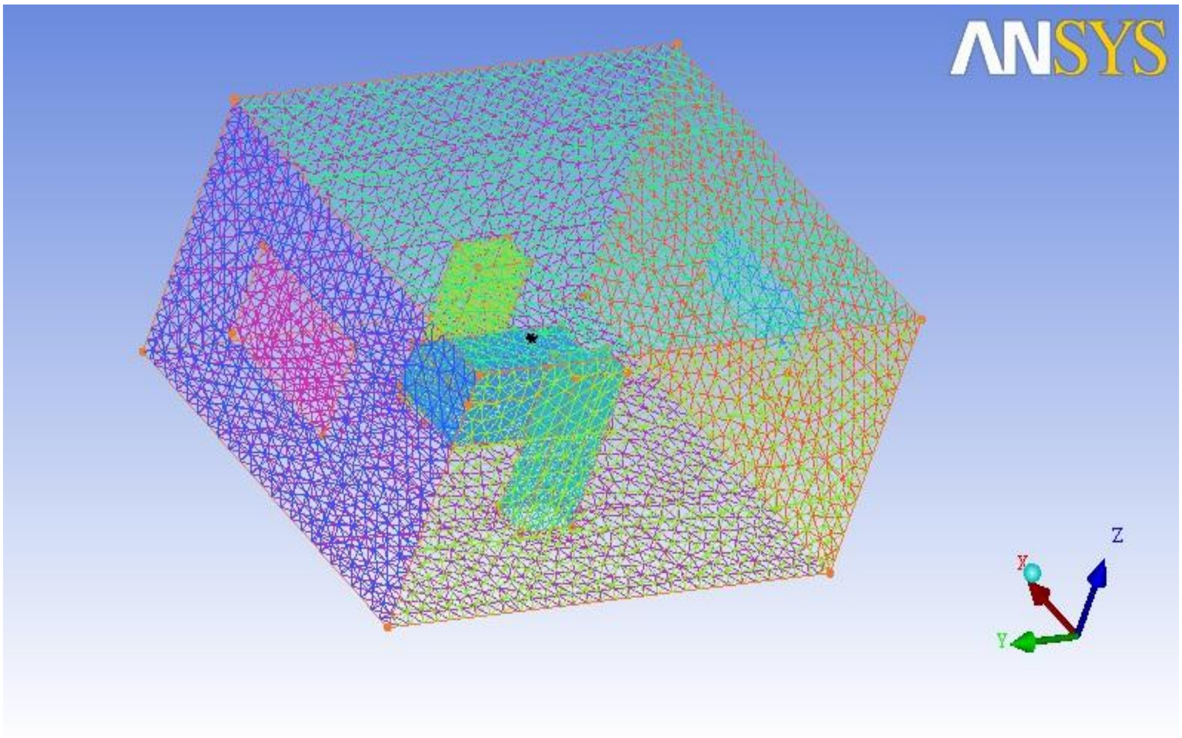


Fig. 2(b) Completed meshing

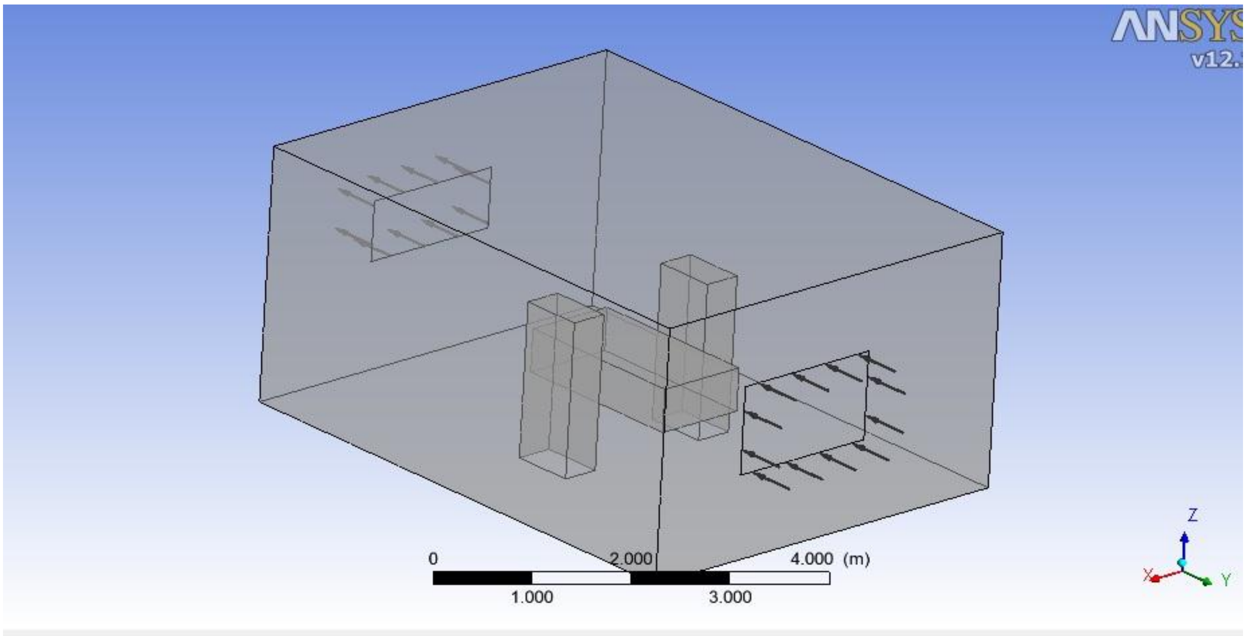


Fig. 2(c) The different boundary, body, inlet, outlet, patient & Doctors have defined before simulation

5.4 Test Simulation

A test simulation was done after meshing in ANSYS CFX Post.

- ✓ We set the inlet boundary condition is 0.8 m³/s air flow rate, 25˚c temperature & atmospheric pressure.
- ✓ Outlet condition is atmospheric.

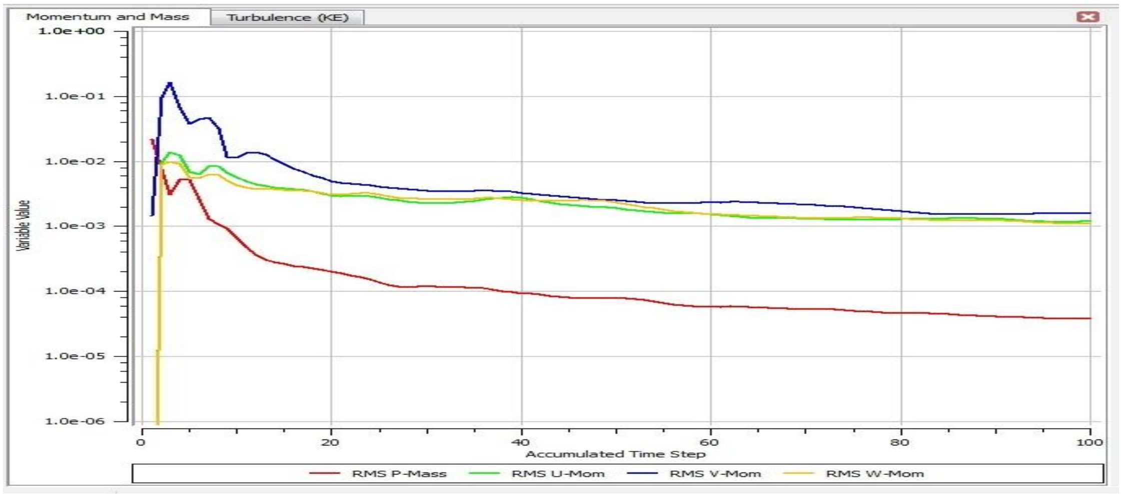


Fig. 2(d) CFX Solver result

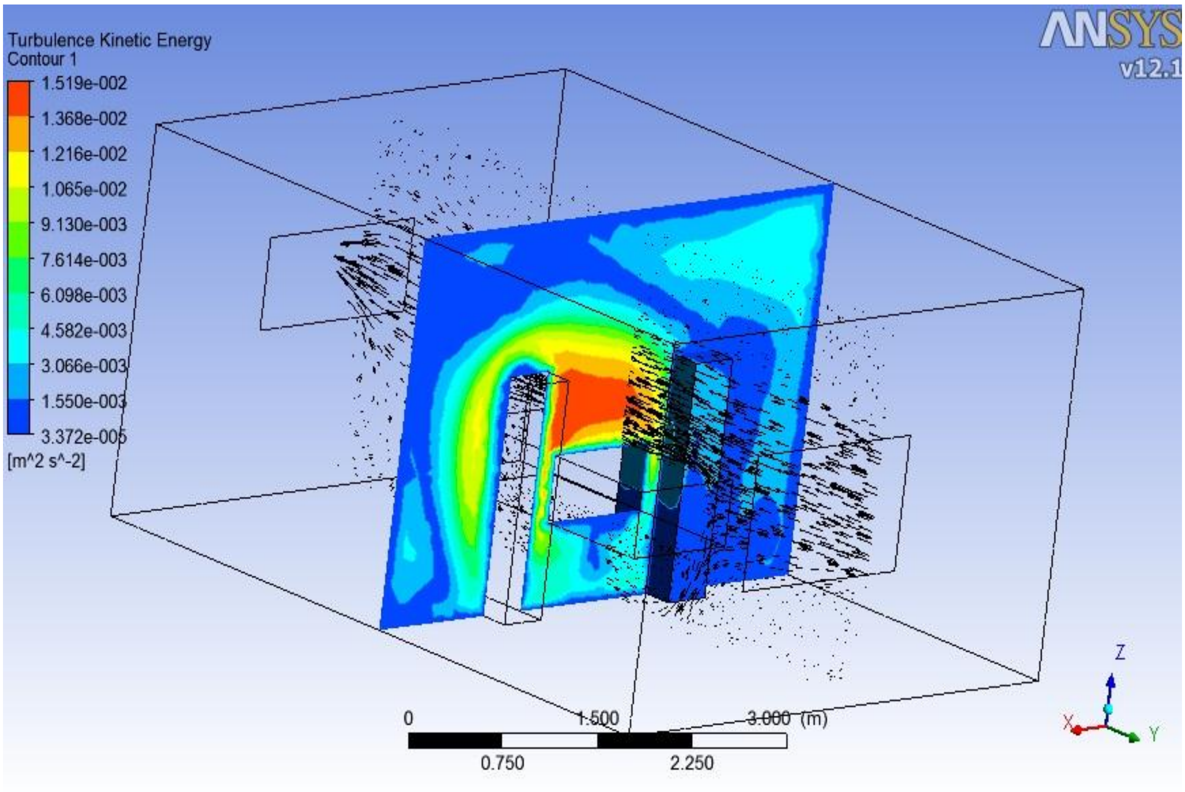


Fig. 2(e) Turbulence Kinetic Energy (plane 1)

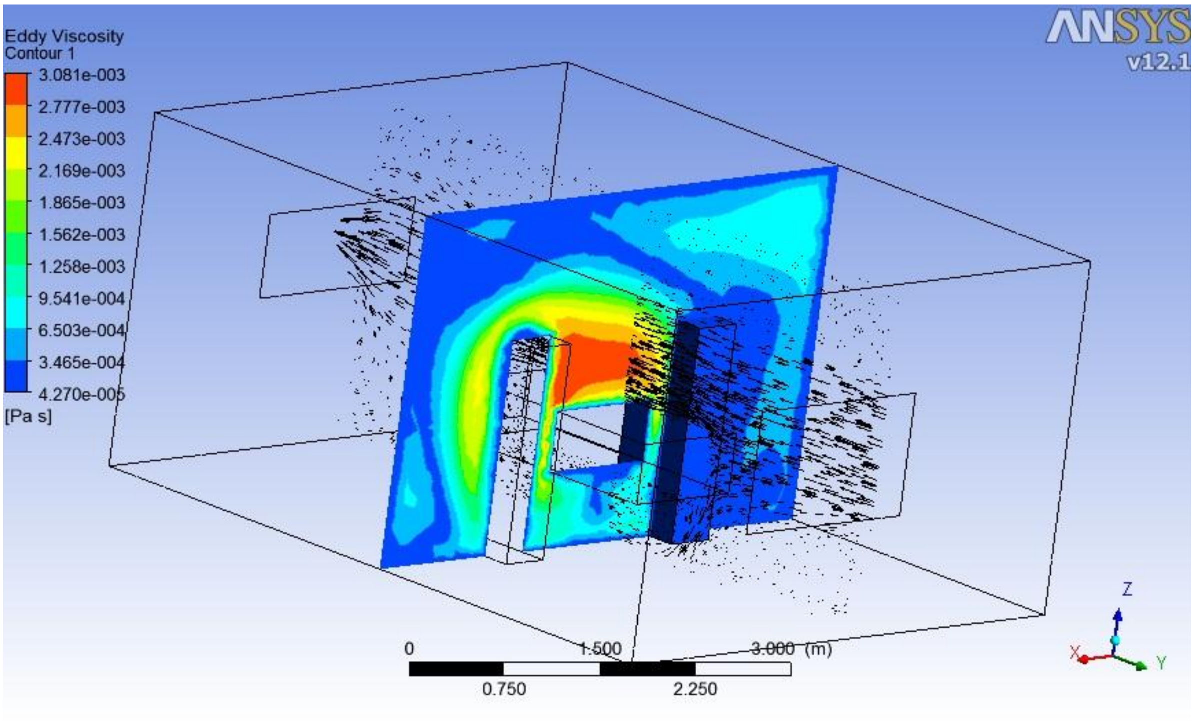


Fig. 2(f) Eddy viscosity profile (plane 1)

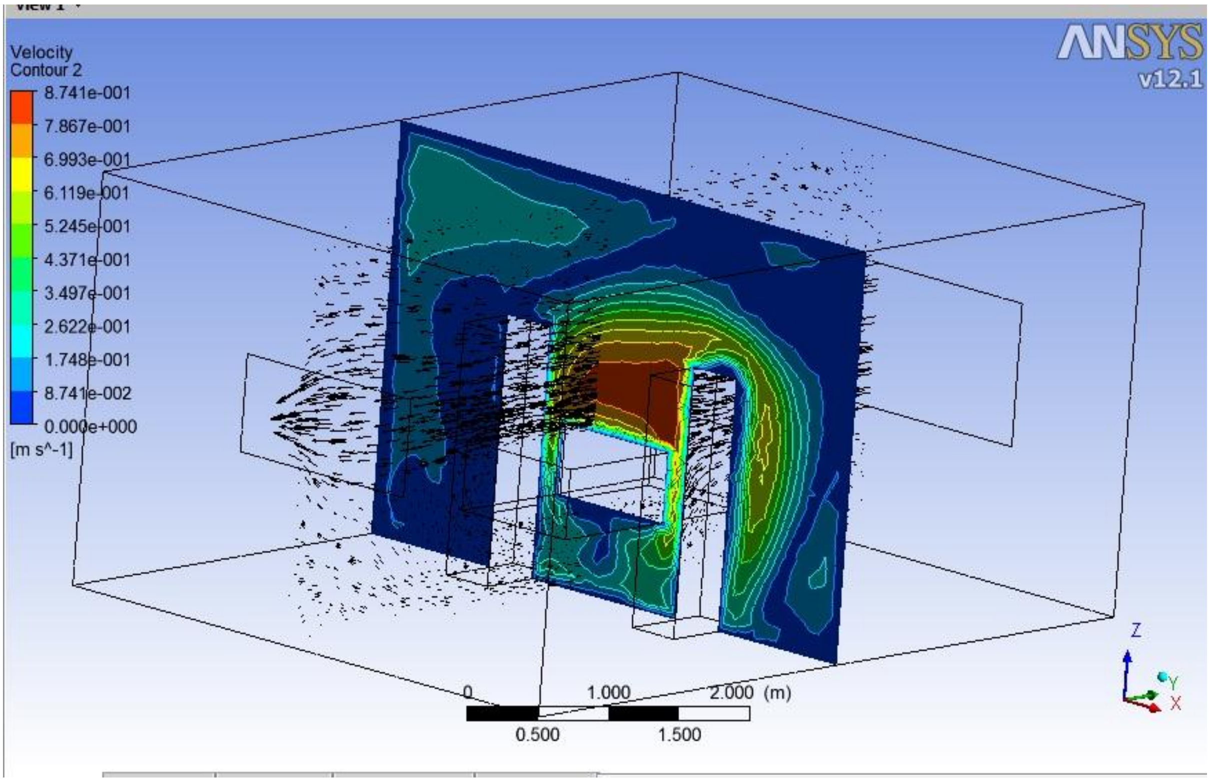


Fig. 2(g) Velocity Contour (plane 2)

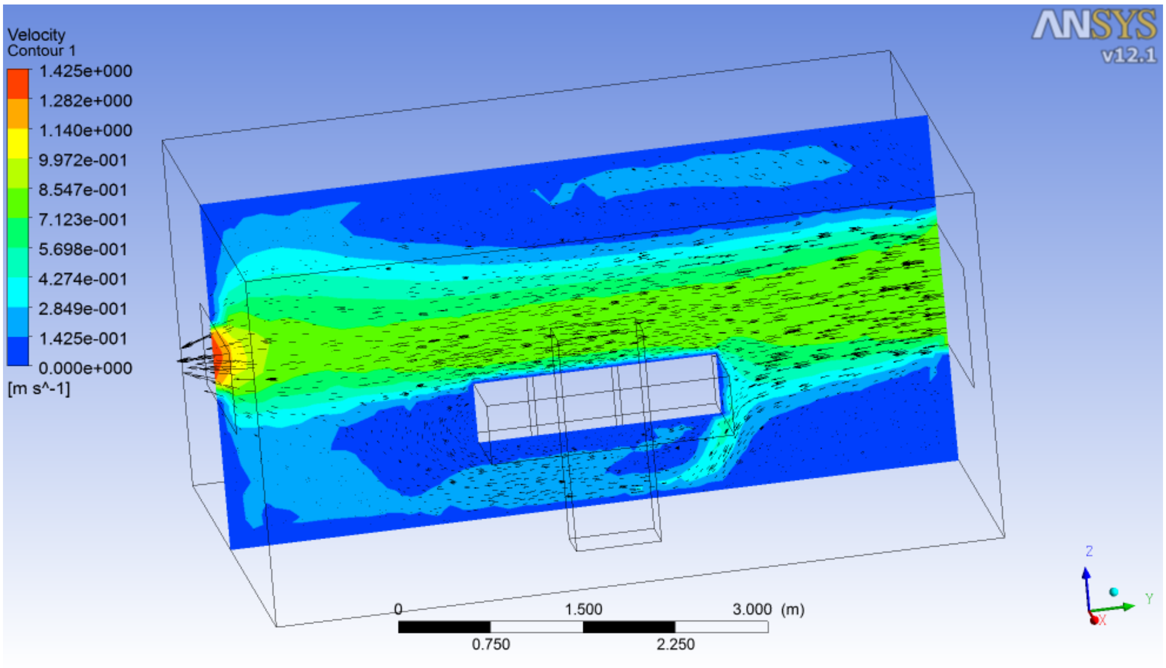


Fig. 2(h) Velocity Contour (plane 1)

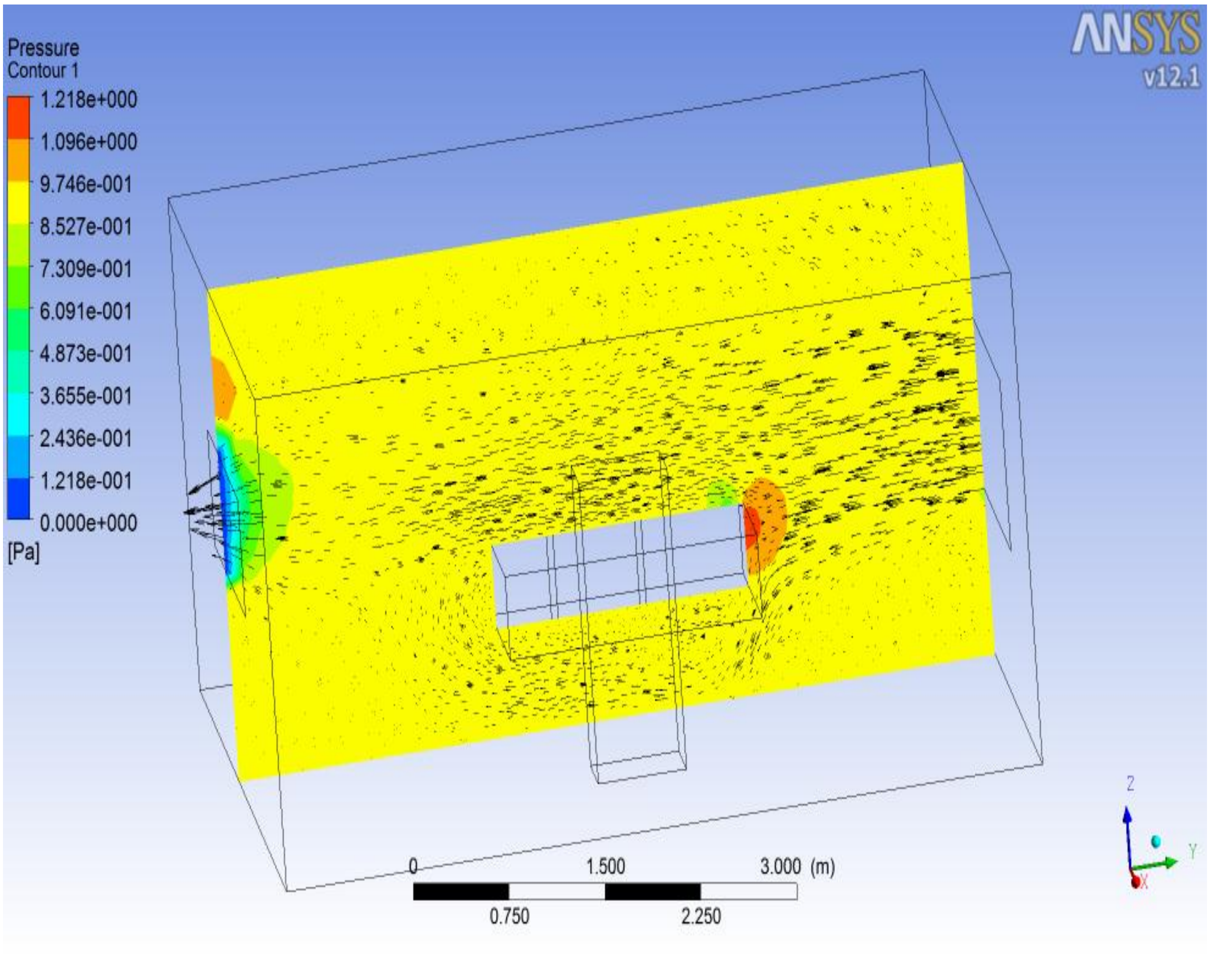


Fig. 2(i) **Pressure Contour (plane 2)**

Chapter 6

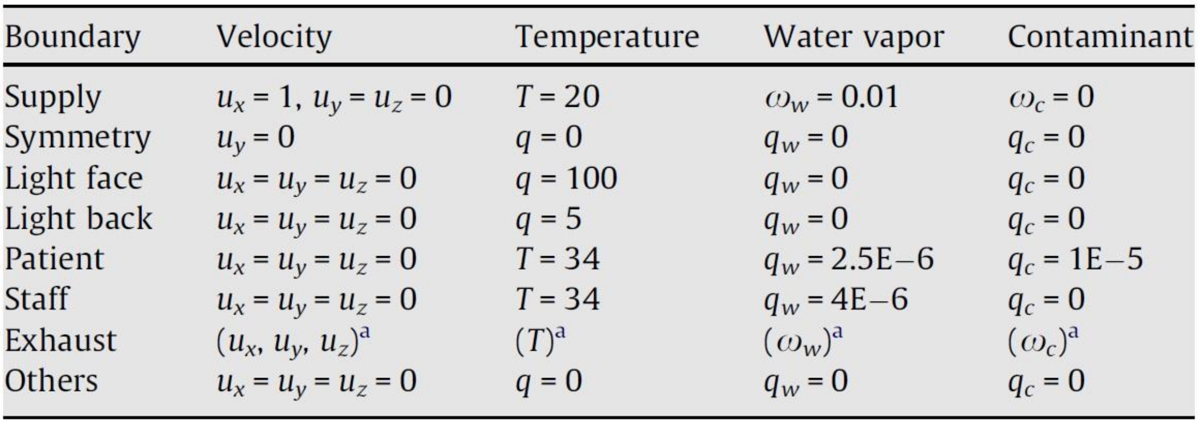
Numerical model and solution

6.1 Input Parameter

An operating room of dimensions 6.1 m * 4.3 m * 3.0 m (20 ft * 14 ft * 10 ft) is considered which has the basic arrangement as shown in Fig. 1a. All the supply and exhaust grilles have the same size of 0.61 m * 0.36 m (24 in. * 14 in). This room can be modeled at full scale with proper consideration. It can be observed that there is a plane of symmetry for the geometry of the room (and the subjects inside) as well as applicable physical conditions and boundary conditions. Due to this symmetry, only a half of the room needs to be modeled. Fig. 1b shows that the room in half is modeled as a three-dimensional box (6.1 m * 2.15 m * 3.0 m) that has six boundary planes namely plane of symmetry, floor, ceiling, and three walls (left, right and side walls). An x–y–z coordinate system is attached to the model with the origin located at the bottom left corner on the plane of symmetry as shown in Fig. 1b. The lying patient in half is modeled as a horizontal rectangular box (1.7 m _ 0.25 m _ 0.3 m) in the middle of the room. Its bottom surface facing the floor models the operating table, which is heat and mass insulated. The other five surfaces model the patient's body, which is maintained at constant temperature and releasing water vapor and contaminant as constant fluxes. The standing surgical staff members are modeled by vertical rectangular boxes at the both ends (staff members 1 and 2, both in half, 0.3 m * 0.25 m * 1.7 m) and by the side of the patient (staff member 3, in full, 0.5 m * 0.3 m * 1.7 m). Similar to the patient's model, these staff member models are considered as surfaces of constant temperature and constant water vapor flux but no contaminant flux. The surgical light is also modeled as a rectangular box (0.7 m * 0.65 m * 0.3 m) above the patient, whose bottom surface (facing the patient) is defined as ‘‘lamp face” entity, on which the major heat flux goes through; and other surfaces are defined as ‘‘lamp back” entity, on which a smaller heat flux goes through.. The other boundary conditions left unmentioned are assumed to be zero velocity and totally insulated to heat and mass (e.g. zero velocity and neither heat flux nor mass flux at solid surfaces such as walls, floor, and ceiling; no contaminant flux from the staffs' body, etc.). Numerical values of the boundary conditions used for the solution are listed in Table 1.

Table 1

Boundary conditions



Boundary	Velocity	Temperature	Water vapor	Contaminant
Supply	$u_x = 1, u_y = u_z = 0$	$T = 20$	$\omega_w = 0.01$	$\omega_c = 0$
Symmetry	$u_y = 0$	$q = 0$	$q_w = 0$	$q_c = 0$
Light face	$u_x = u_y = u_z = 0$	$q = 100$	$q_w = 0$	$q_c = 0$
Light back	$u_x = u_y = u_z = 0$	$q = 5$	$q_w = 0$	$q_c = 0$
Patient	$u_x = u_y = u_z = 0$	$T = 34$	$q_w = 2.5E{-}6$	$q_c = 1E{-}5$
Staff	$u_x = u_y = u_z = 0$	$T = 34$	$q_w = 4E{-}6$	$q_c = 0$
Exhaust	$(u_x, u_y, u_z)^a$	$(T)^a$	$(\omega_w)^a$	$(\omega_c)^a$
Others	$u_x = u_y = u_z = 0$	$q = 0$	$q_w = 0$	$q_c = 0$

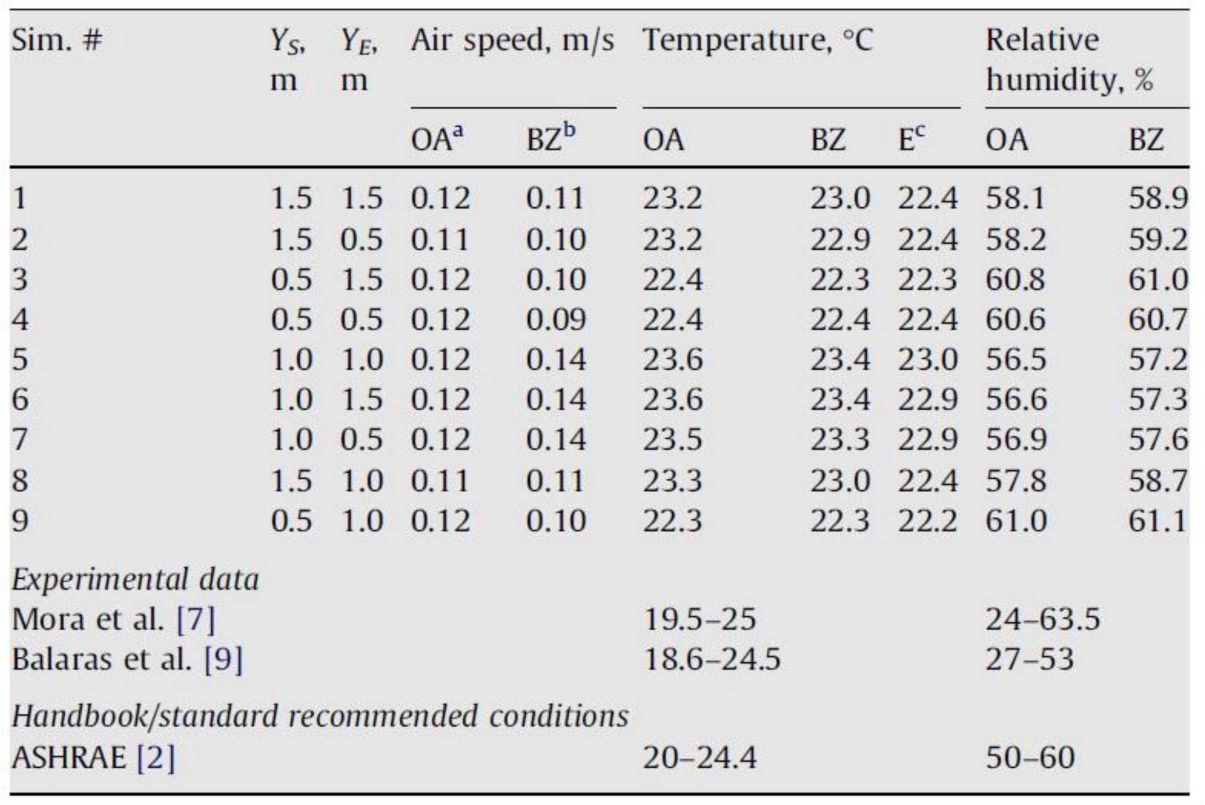
The supply grille is located at a high position on the left wall. Its center is given by the coordinates YS (from the plane of symmetry) and ZS = 2.45 m (from the floor). The exhaust grille is placed at a low position on the right wall. Its center is given by the coordinates YE (from the plane of symmetry) and ZE = 0.55 m (from the floor).

The effects of the horizontal locations of the supply and exhaust grilles (YS and YE) are studied by running simulations with various combinations of these coordinates. In order to estimate the influence of these two factors on the response of interest (CRE, PMV, etc.), the method of design of experiment (DOE) is adopted.

Since the number of factors is only two, full factorial design is used for better design resolution. For two-level experimental design, two numerical values (low, high) can be assigned to each factor to get a total of four experiments (simulations). For three-level experimental design, three numerical values (low, medium, high) can be assigned to each factor to get a total of nine experiments (simulations). The experimental values for both factors are selected as: low = 0.5 m, medium = 1.0 m, high = 1.5 m. Nine simulation cases are summarized in the first three columns of the first section of Table 2.

Table 2

Simulation cases and mean values of air speed, temperature, and relative humidity.



Sim. #	Y_S, m	Y_E, m	Air speed, m/s		Temperature, °C			Relative humidity, %	
			OA[a]	BZ[b]	OA	BZ	E[c]	OA	BZ
1	1.5	1.5	0.12	0.11	23.2	23.0	22.4	58.1	58.9
2	1.5	0.5	0.11	0.10	23.2	22.9	22.4	58.2	59.2
3	0.5	1.5	0.12	0.10	22.4	22.3	22.3	60.8	61.0
4	0.5	0.5	0.12	0.09	22.4	22.4	22.4	60.6	60.7
5	1.0	1.0	0.12	0.14	23.6	23.4	23.0	56.5	57.2
6	1.0	1.5	0.12	0.14	23.6	23.4	22.9	56.6	57.3
7	1.0	0.5	0.12	0.14	23.5	23.3	22.9	56.9	57.6
8	1.5	1.0	0.11	0.11	23.3	23.0	22.4	57.8	58.7
9	0.5	1.0	0.12	0.10	22.3	22.3	22.2	61.0	61.1
Experimental data									
Mora et al. [7]					19.5–25			24–63.5	
Balaras et al. [9]					18.6–24.5			27–53	
Handbook/standard recommended conditions									
ASHRAE [2]					20–24.4			50–60	

Simulations 1–4 represent the two-level design, and simulations 1–9, the three-level design. Comprehensible concepts of DOE can be found in conveniently available online. More fundamental explanation can be found in the classic textbook by Box et al.

6.2 Addition of Heat Flux

- In an Operation theater the major heat source is the surgical operation light. For thermal comfort we have to consider the heat removal of the surgical light.
- We consider the heat flux from the surgical light is 300w/m²
- Heat Flux from the Human body is considered as 100w/m²

6.3 Addition of Contaminant Source

- A Contaminant source is set up on the top of the patient, which emits 50µg of tracer particle per cm^2.
- The tracer particle has size of 10µm & 3 µm

6.4 Fluid Properties Considered

- Reference Temperature, T= 20°C = 293 K
- Air Density, $\rho = 1.2$ kg/m^3
- Viscosity of air, $\mu = 1.8 \times 10^{-5}$ kg/(ms)
- Thermal Expansion co-efficient, $\beta = 0.0034$ K^{-1}
- Specific Heat of Air, $C_p = 1004$ J/(KgK)
- Thermal Conductivity of Air, k = 0.026 W/(mk)
- $Dw/a=2.5*10^{-5}$ m^2/s
- $Dc/a = 1.2 *10^{-5}$ m^2/s.

For each simulation, the governing Equation (1) – (5) with associated boundary conditions is numerically solved by employing the finite-element method with the use of the commercial CFD analysis software package FIDAP. First, the computational domain is discredited (subdivided) into a mesh of many elements. The mesh generation software GAMBIT is used for this purpose. The distribution of element size in the computational domain is determined from a mesh independence study by systematically changing the mesh density in all space directions both globally and locally to obtain a mesh that can give a numerical solution independent of the number of elements with acceptable accuracy.

Regular elements are used to fill most parts of the domain while properly refined element layers are assigned around inlet, outlet, and solid surfaces to capture the high rates of change of momentum and heat transfer that exist there. In each element, velocity components, pressure, temperature, water vapor and contaminant concentrations are approximated by using the Galerkin procedure, which leads to a set of algebraic equations defining the discredited continuum. A segregated algorithm is used to solve the nonlinear system of finite algebraic equations. The iterative procedure for the solution is considered converged when the norm of the relative errors of the solution between iterative steps is less than a tolerance of 0.01. The numerical solution includes the values of three velocity components, pressure, temperature, and concentrations of water vapor and contaminant at every nodal point of the computational domain. From the relevant variables, relative humidity is computed by using Equation (6)–(8), PMV by Equation. (9) – (13), and CRE by Eq. (14).

For the mesh independence study, different cases of mesh size are considered. Each case is represented by a nominal element size chosen among the values 0.2 m, 0.15 m, 0.125 m, 0.1 m, 0.075 m, and 0.05 m. These nominal element sizes result in the corresponding meshes with the number of elements of 12,166, 25,742, 42,200, 56,042, 143,752, and 364,040. Fig. 2 shows how the representative air temperature in the room becomes independent from the mesh as the number of elements increases (the nominal element size decreases).

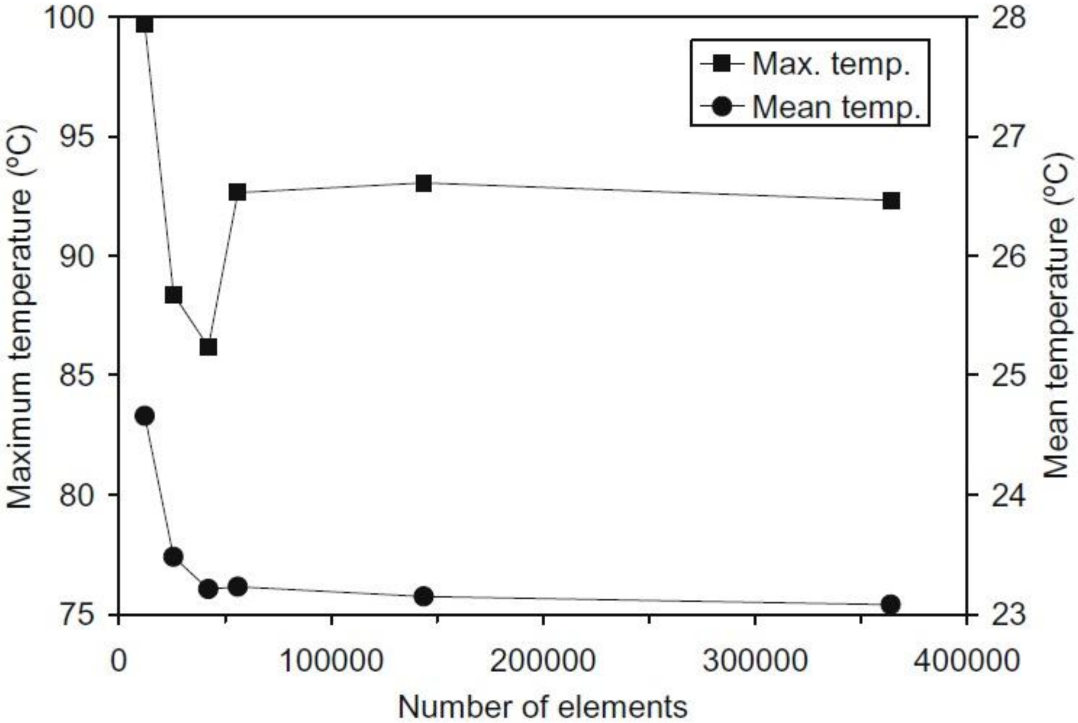


Fig. 2(j) Grid independence study

Fig. 2 presents the values of maximum temperature and mean temperature as functions of the number of elements. It demonstrates that as the number of elements increases over 50,000, mesh independence of the numerical solution is achieved.

Chapter 7

Final Results

Final Results:

Fig. 3 presents the distribution of the variables of interest for simulation 1. Fig. 3a presents the distribution of air speed by displaying respective interpolated filled color on orthogonal slice planes. The slice planes, selected in such a way that can reveal the structure of the volumetric data, include planes through the center of the grilles and the obstacles. Fig. 3b shows the three-dimensional streamlines which begin at nine representative starting points on the area of the supply opening. These streamlines are numbered from 1 to 9 with color coded legend for easily tracing their paths. Fig. 3a and b can be examined simultaneously to view the image of the flow field in the domain. The cold airflow enters the room at full speed (1 m/s) through the supply opening located at a high position on the left wall. The colder air, having higher density, goes down smoothly as shown in both Fig. 3a and b for all streamlines. While going down, the supply airflow loses speed and spreads wider as it reaches the floor. As the driving force depletes when the airflow touches the floor, it becomes influenced by lower pressure at the exhaust opening. Under this influence, most of the main airflow is pulled toward and exits through the exhaust opening at increasing speed in a curling move as shown in Fig. 3b due to the nature of airflow of being not capable of making abrupt turns. A small part of the main airflow is influenced by the complex driving forces including the buoyancy effect in the hotter region close to the occupants' bodies. The flow can go up and down and travels back and forth in the room, between the occupants' bodies, at somewhat lower speed. Generally, it can be observed in Fig. 3b that more disturbances (thus better air mixing) exist in the lower part of the exhaust side of the room.

Fig. 3c presents the isosurface plot for pressure distribution. The value of air pressure is the same on an isosurface. It can be observed that most of the isosurfaces are almost flat, well layered, and perpendicular to the vertical direction. This pattern implies that vertical flow thus free convection dominates the airflow. The effect of forced convection (horizontal direction) can only be observed in the region close to the supply opening where the isosurfaces are no longer flat but have high curvature. There are also slight disturbances on the isosurfaces in the regions near the floor or non-slip interfaces (occupants' bodies).

Fig. 3d shows the slice planes plot for the distribution of contaminant concentration in the domain. This contaminant is driven out by the concentration gradient from the patient to the surrounding, mainly by diffusion and natural convection to the outside of the surgical field, and then gets carried away by the forced main airflow to the exhaust opening. The high contaminant concentration exists in the surgical site and near the ceiling while the lower part of the room has low contaminant concentration. The pattern of diffusive transport (gradually varying concentration) can be observed between these two regions.

Fig. 3e is the slice planes plot of temperature distribution for simulation 1. Wherever the air speed is high, such as in the main airflow or in the circulations close to the exhaust opening, the temperature is lower due to low temperature in the supply air itself or by well mixing it with the heated air inside the room. The main airflow creates a low temperature region next to the supply opening where the cold air enters the room and has not picked up much heat in the room yet. In the surgical field, heat released from the lights induces natural convection flows that carry the heat up to the ceiling, resulting in a region of higher temperature there. The heat transfer around the occupants' bodies takes place by diffusion and natural convection. The region of high temperature (24°C and higher) spreads in the higher part of the room and covers most of the ceiling area with not much uniform distribution. The lower part of the room has a lower temperature (23°C and less) but of more uniform distribution. A region of medium temperature (23–24°C) exists in the activity space of the occupants (at a height of 1–2 m).

Fig. 3f is the plot of relative humidity distribution, a key factor of thermal comfort. Relative humidity is a function of absolute pressure, water vapor concentration, and temperature. Relative humidity is computed by using Equations. (6) – (8). Since the room gage pressure is found very small (on the order of 1 Pa as shown in (Fig. 3c), compared to the atmosphere pressure (as high as 101 kPa), it does not significantly affect the total (absolute) pressure, and thus almost does not affect the values of relative humidity. Wherever low temperature and high water vapor concentration exist, relative humidity is also high. Near the surgical lights, the relative humidity is very low because of high temperature. Inverse to the temperature distribution, high humidity region exists in the lower part of the room and low humidity exists in the higher part of the room.

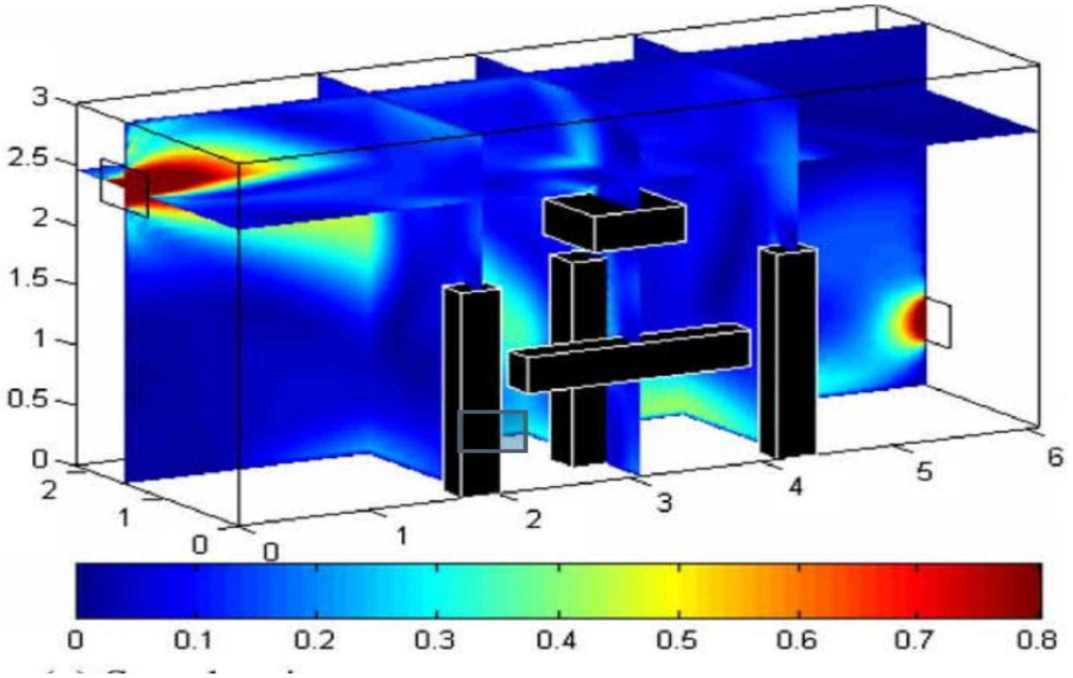


Fig. 3 (a) Speed, m/s

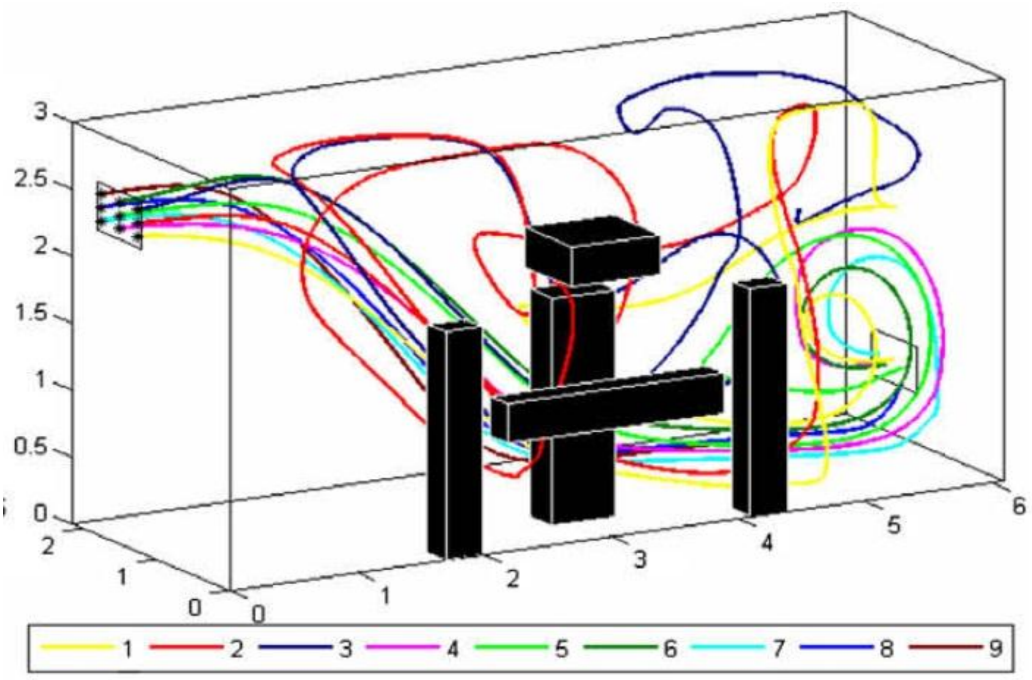


Fig. 3 (b) Streamlines

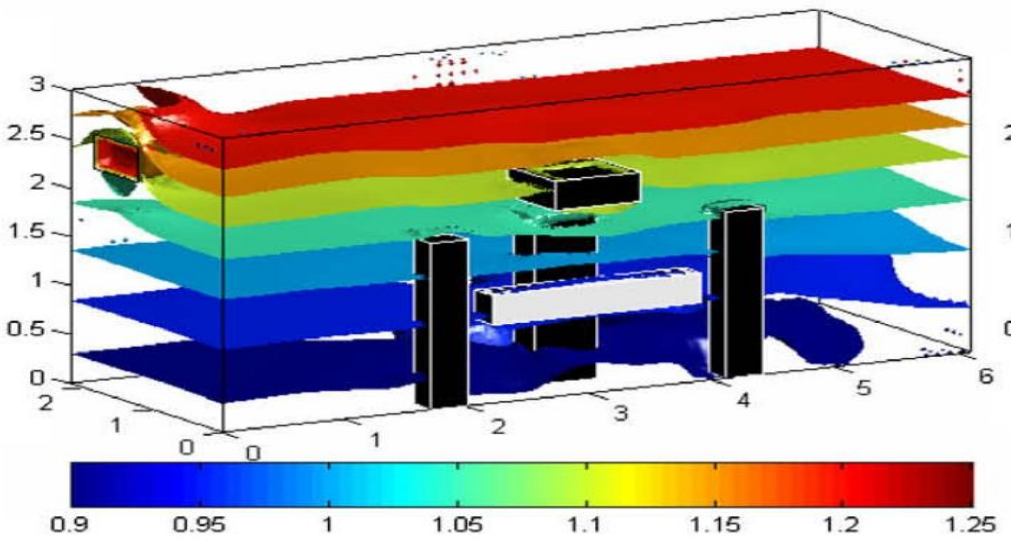


Fig. 3 (c) Pressure, Pa

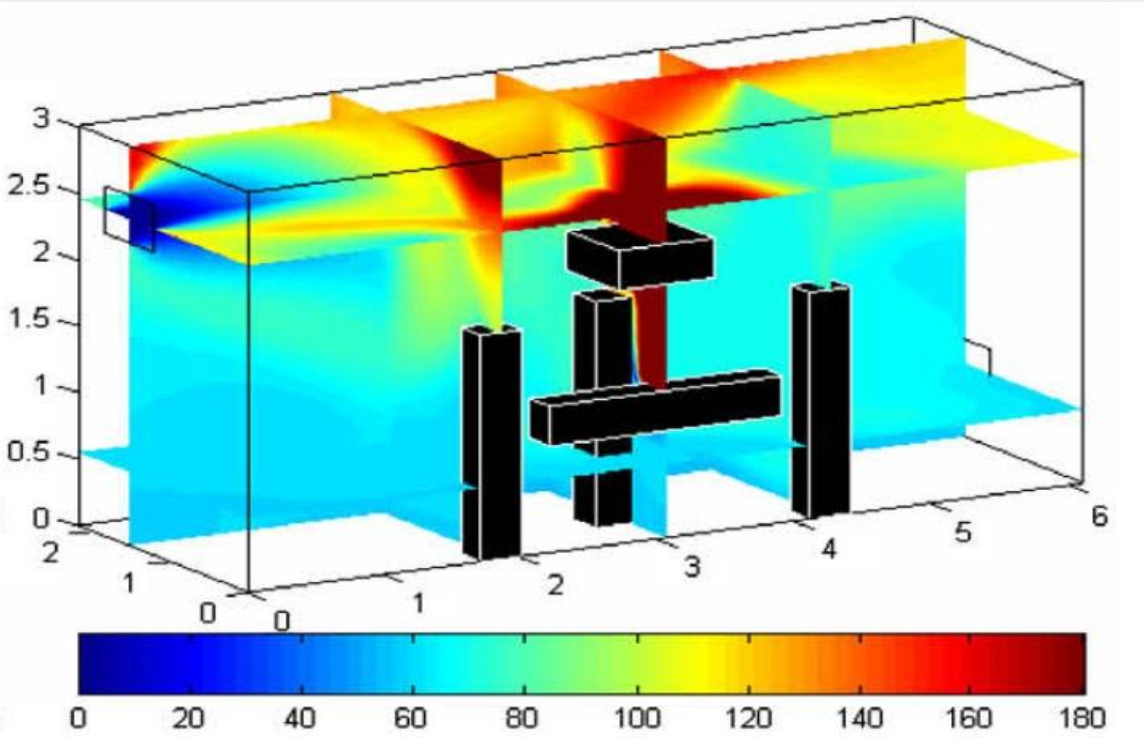


Fig. 3 (d) Contaminant Concentration, mg/kg

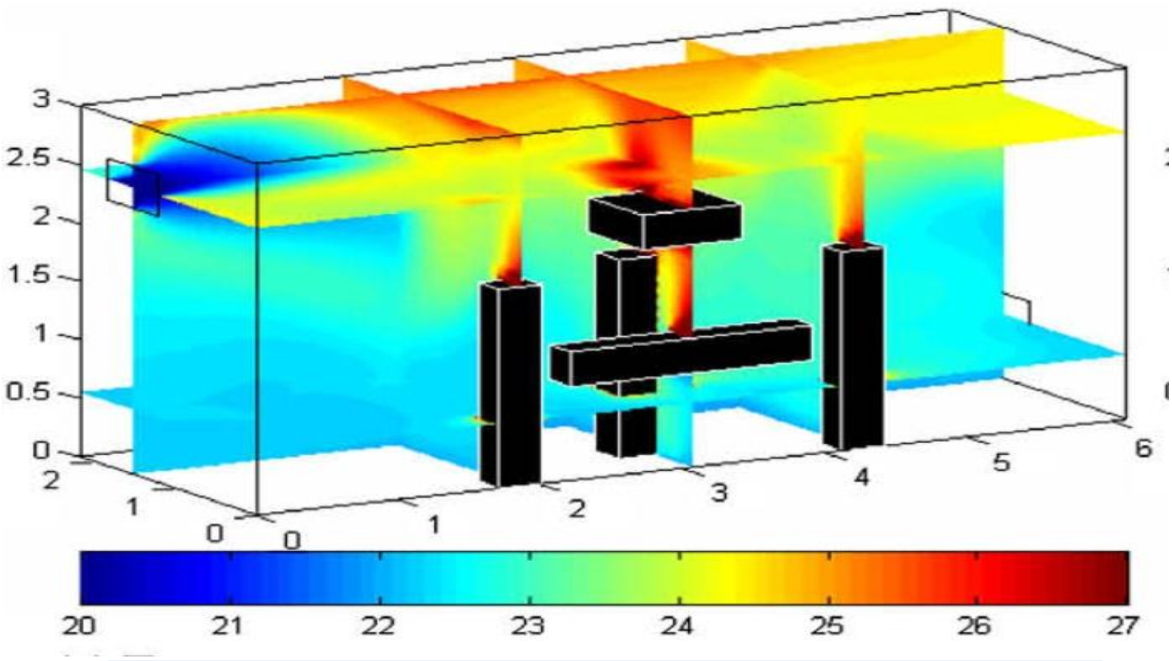


Fig. 3 (e) Temperature, °C

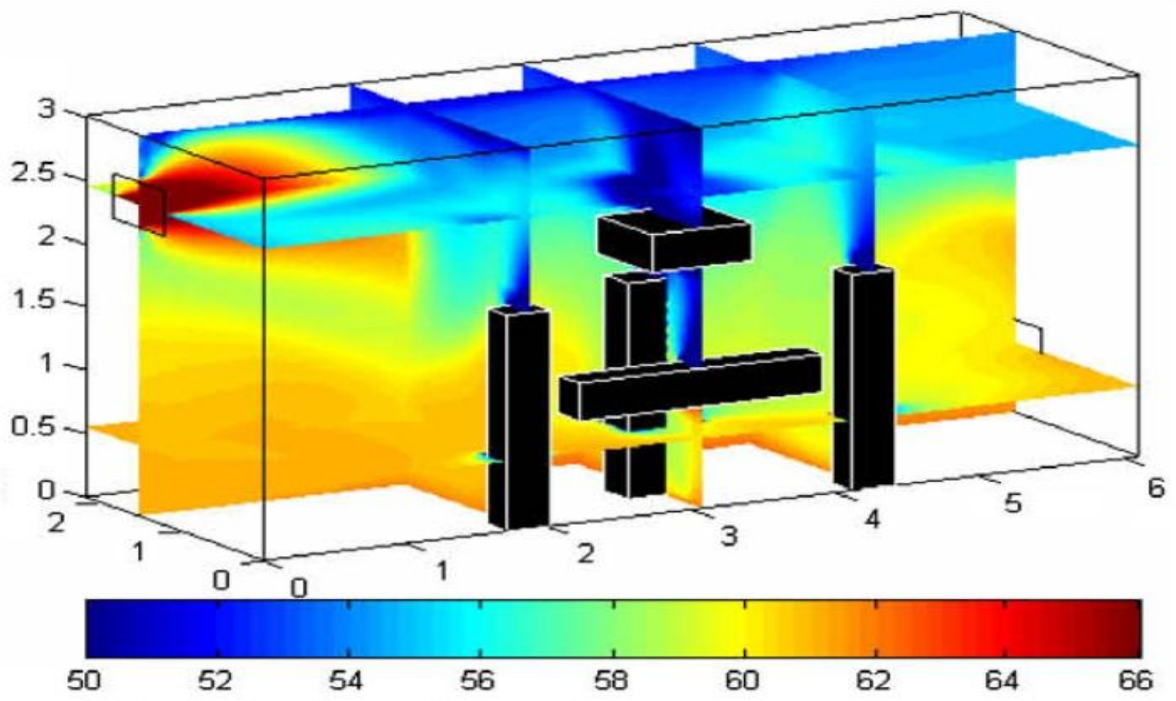


Fig. 3 (f) Relative Humidity, %

Fig. 3. Distributions of air velocity, pressure, contaminant concentration, temperature, and relative humidity for simulation 1 (Y_S = 1.5 m, Y_E = 1.5 m).

The mean values of air speed, temperature, and relative humidity can be used for a quick assessment of the thermal comfort condition of a room. The mean values are taken over both the entire domain (overall – OA) and the occupied zone (considered the same as the breathing zone – BZ). For temperature, there are mean values taken over the exhaust opening area (E) as well. Beside of being able to intuitively represent the thermal comfort condition of the occupants, these mean values also show a clearer trend of how they change as the design factors change. Table 2 shows a summary of these basic thermal comfort parameters for all simulation cases. The mean air speed varies in the range 0.10–0.14 m/s, about a tenth of the nominal supply speed; mean temperature varies in the range 22.2–23.6 °C, which is 2–4 °C higher than the supply temperature (20 °C); mean relative humidity varies in the range 57–61%. For each simulation, the difference of mean air speed in OA and BZ is about 0.01–0.02 m/s, which is not a significant amount. The difference of mean temperature in OA and BZ can be up to 0.3 °C, while the exhaust temperature can have a difference of up to 0.9 °C, both cases are quite significant for thermal comfort. The difference of mean relative humidity in OA and BZ is less than 1%. These observations suggest that for a simple assessment of thermal comfort, mean air speed and mean relative humidity taken over either OA or BZ can be used without much difference while it is best to use mean temperature taken over BZ since that is closer to the condition of the occupants. Temperature is obviously the most important criterion for a simple assessment of thermal comfort. In a cooling situation, the lower the temperature the better thermal comfort condition is. It can be observed in Table 2 that lowest mean temperature appears in the results of simulations 3, 4, and 9 (22.3– 22.4°C in all three columns OA, BZ, and E). It occurs that for the minimum temperature case the exhaust temperature is very close to the bulk temperature (either BZ or OA) while it is not for the other cases. All of those simulations (3, 4, and 9) have YS = 0.5 m. It is also found that mean temperatures are very close within each of the following groups of simulations: {1, 2, and 8} (22.9–23.0°C in BZ, YS = 1.5 m) and {5, 6, and 7} (23.3–23.4°C) in BZ, YS = 1.0 m). The observation suggests that the horizontal location of the supply grille YS is highly significant to temperature and the smaller the value of YS, the cooler it is. In Table 2, mean temperature and relative humidity are also compared to experimental data from actual hospital operating rooms given by Mora et al. [7] and Balaras et al. [9]. The data from [7] and [9] are collected from 2 and 20 operating rooms, respectively. The mean temperature and relative humidity from the numerical simulation show a reasonably good agreement with experimental data. These mean computational values in all cases are also within the recommended ranges specified by ASHRAE.

Fig. 4 presents the computational results for simulation 3 which is in the group of simulations with YS = 0.5 m that give the best cooling performance as found previously. Fig. 4a and b for air speed and streamlines show that the supply airflow moves horizontally without dropping down as in simulation 1. This happens because of the heat released from the lights and occupants' bodies induces the natural convection flow which forces the heated air up directly into the incoming supply main flow and supports it to move straight. The streamlines plot in Fig. 4b also shows that the supply airflow moves around in the upper part and supply side of the room before exiting through the exhaust opening, resulting in better air mixing in this region. In this simulation, the exiting flow moves from far away straight to the exhaust opening without curling as seen in simulation 1.

The horizontal main airflow shows its effects explicitly on the pressure isosurfaces in Fig. 4c. In the region dominated by the horizontal flow in the supply side and close to the ceiling, the isopressure surfaces have very high curvature, while in the natural convection (vertical flow) dominated region on the exhaust side, the isopressure surfaces have the horizontal flat plate form like simulation 1.

The slice planes plot for contaminant concentration in Fig. 4d shows that the well-mixed air region has positive effects on contaminant removal with very low concentration. Contaminant is concentrated toward the exhaust side of the room close to the ceiling where the air speed is very small as shown in Fig. 4a. From that region down toward the floor, a diffusion pattern exists since convective transport is limited in that region due to the lack of strong airflow. In comparison to simulation 1 since there is stronger airflow reaching into the surgical field, the contaminant in this region is less accumulated. However, high contaminant concentration in front and on top of staff member 2 (standing on the exhaust side of the room) should be taken into consideration.

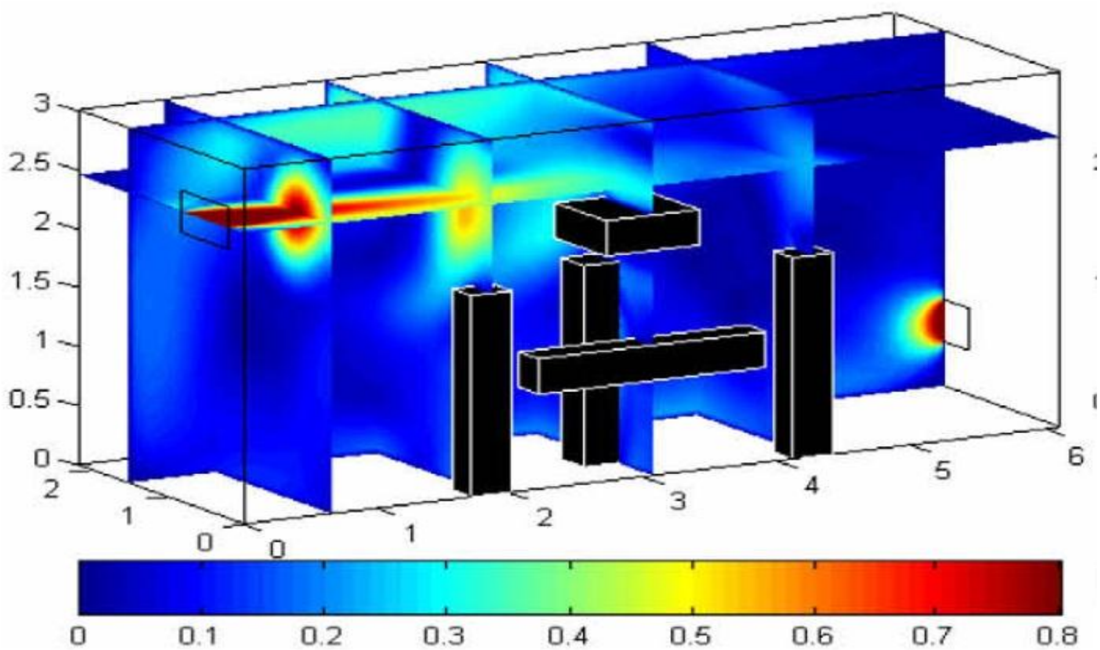


Fig. 4 (a) Speed, m/s

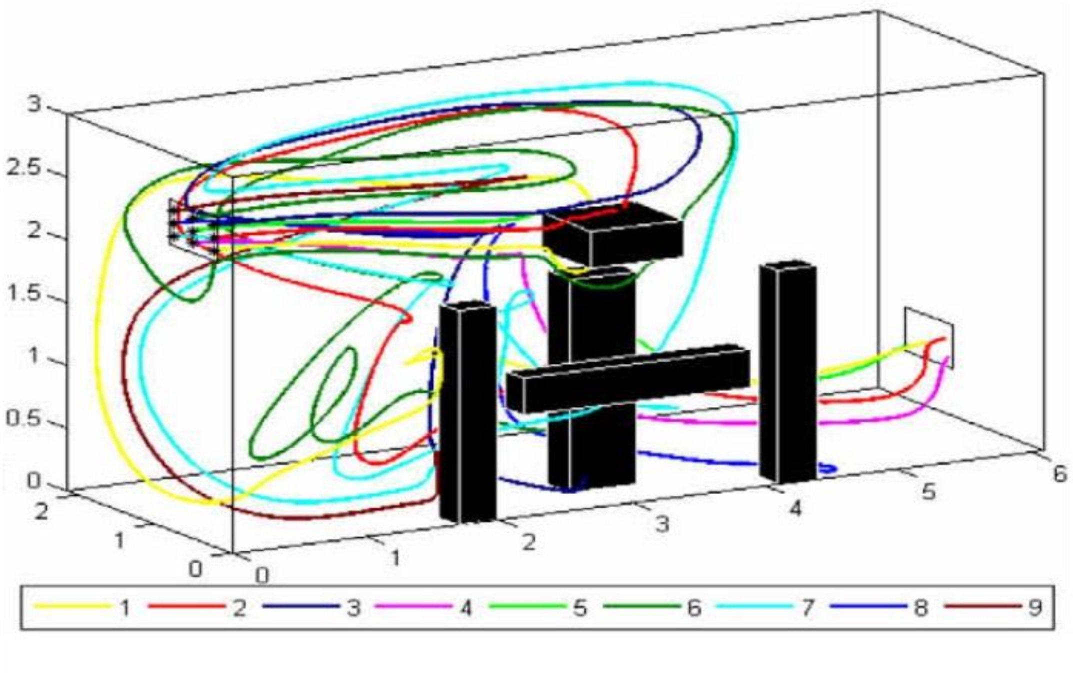


Fig. 4 (b) Streamlines

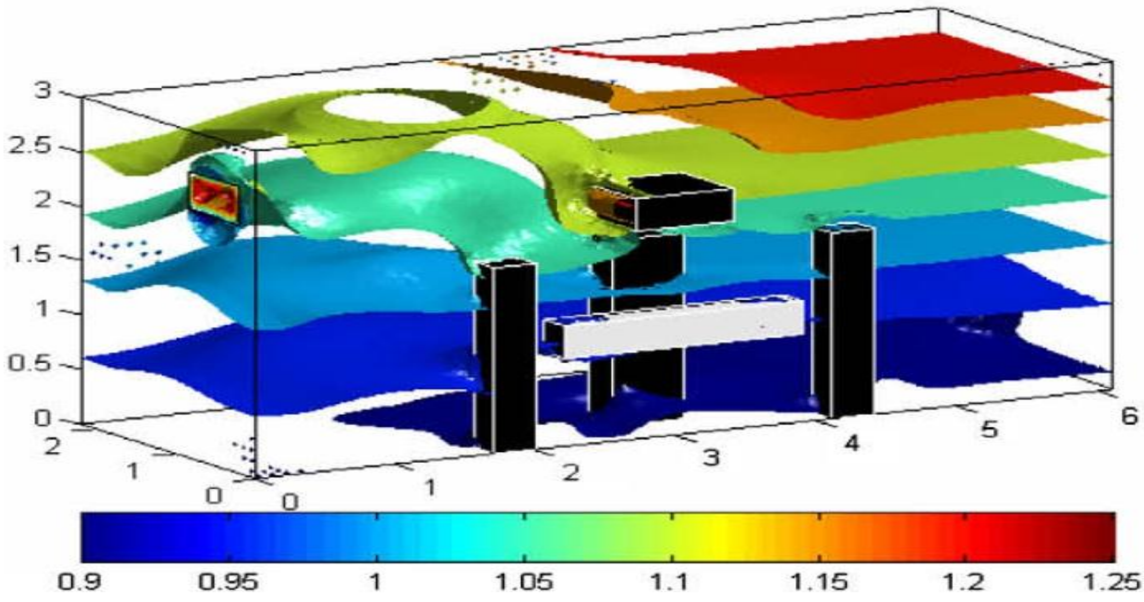


Fig. 4 (c) Pressure, Pa

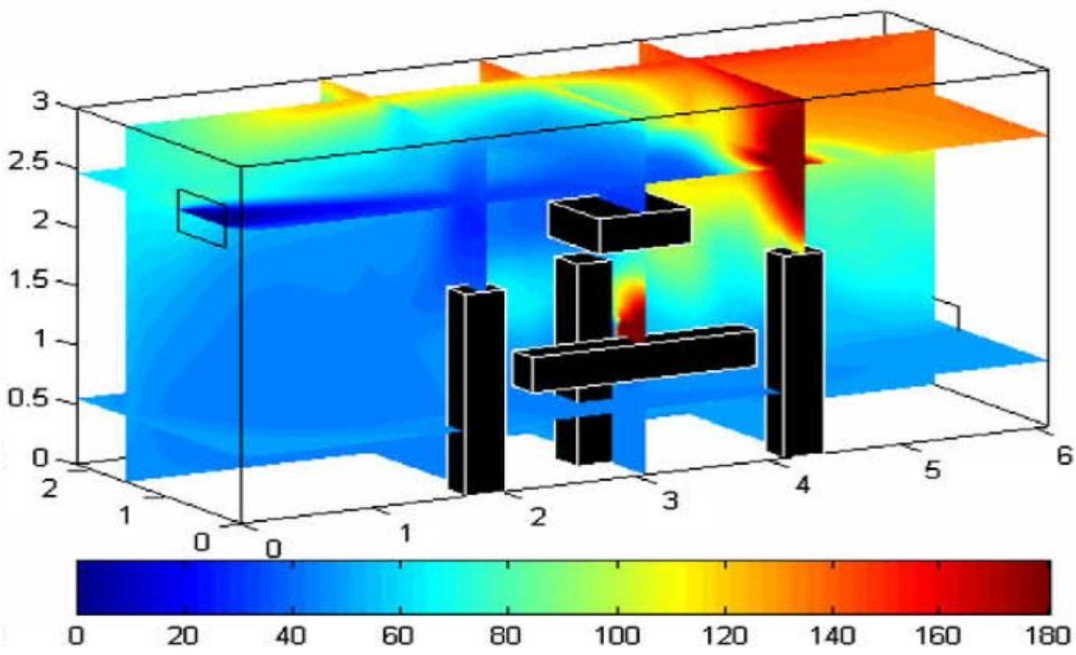


Fig. 4 (d) Contaminant Concentration, mg/kg

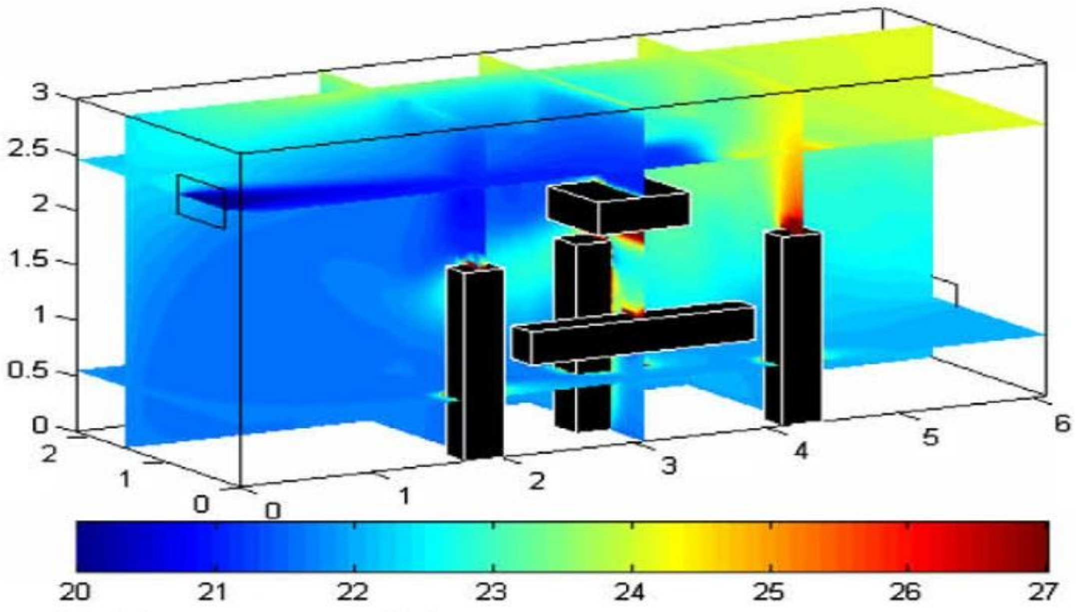


Fig. 4 (e) Temperature, °C

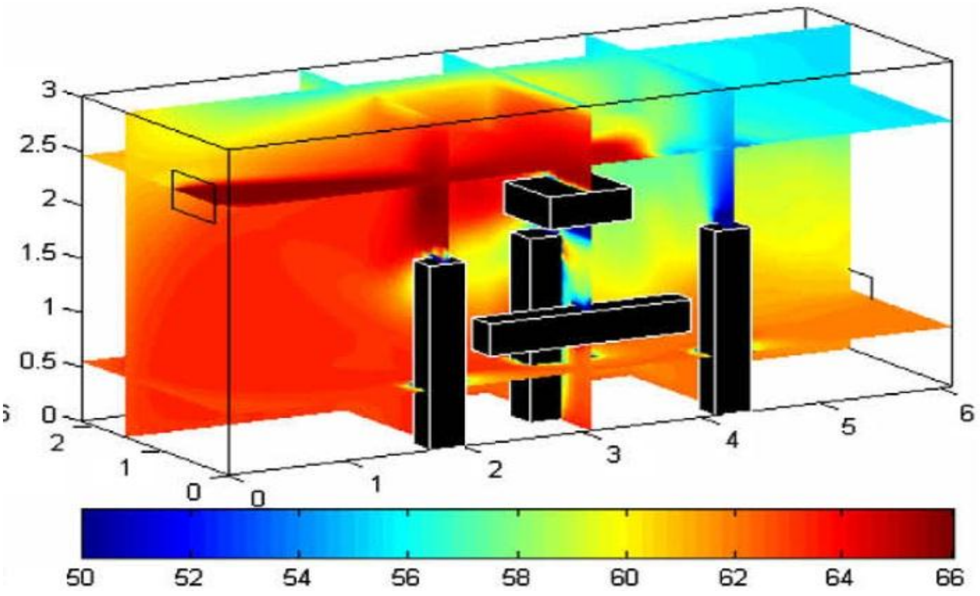
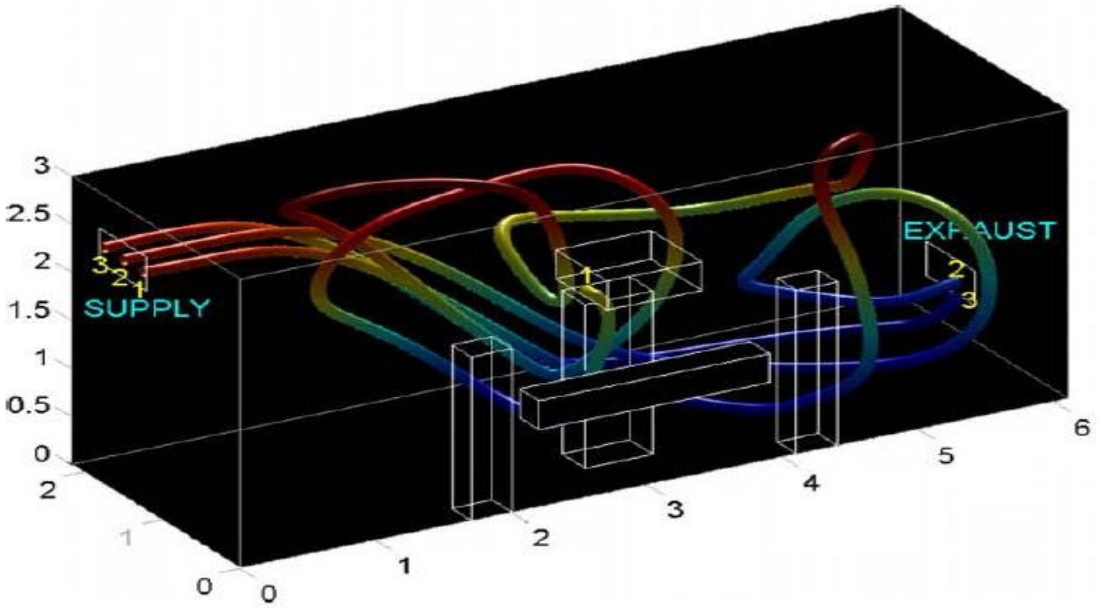
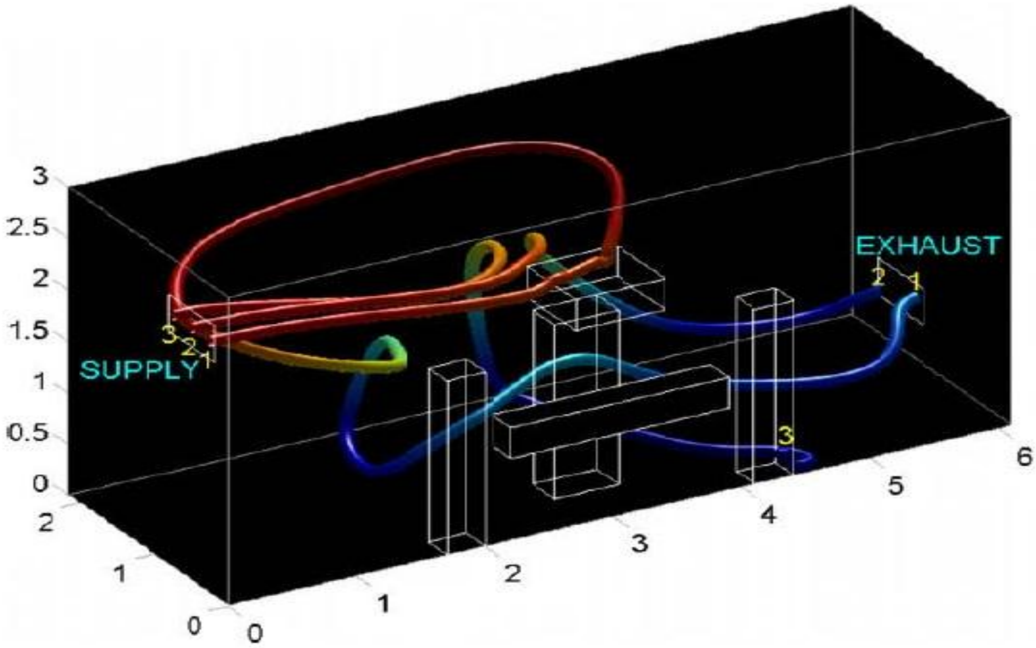


Fig. 4 (f) Relative Humidity, %

Fig. 4. Distributions of air velocity, pressure, contaminant concentration, temperature, and relative humidity for simulation 1 (Y_s = 0.5 m, Y_E = 1.5 m).



Simulation 1



Simulation 3

Fig. 5. Comparison of airflow patterns in simulations 1 and 3.

Fig. 4e shows the temperature distribution for simulation 3. Because of the well-mixed airflow, the region on the supply side has a lower temperature (less than 22 _C). The lower part toward the exhaust side of the room also has a relatively low temperature due tothe effect of the exhausting flow. Scattered small regions of high temperature exist around the lights and bodies. The high temperature region in the upper part on the exhaust side of the room actually has moderate temperature (23–24 °C) as compared to that in simulation 1. Relative humidity distribution in Fig. 4f, again, shows an inverse image of temperature in Fig. 4e. Relative humidity is 62–64% in the well-mixed region and around 56% in the stagnant region occupying the upper part of the exhaust side of the room.

It has been observed that for both simulations 1 and 3, the airflow pattern plays an important role on both thermal comfort and contaminant control. Fig. 5 shows a comparison of the airflow patterns for the two cases by examining their representative stream tubes. For each simulation, the stream tubes originated from three starting points numbered 1 through 3 in the supply opening are plotted. The end of each stream tube is also marked with the same number. In Fig. 5a, all three stream tubes go down at first and then move along separate paths. Stream tube 1 starts closest to the obstacles, moves around the room following a complex path, loses all of its momentum and dies out inside the room. Stream tube 2 makes a curl before exiting through the exhaust opening and stream tube 3 exits straight. In Fig. 5b, the flow patterns are different. All three stream tubes move straight at first, but it can be observed that as the starting point gets farther away from the central region, the stream tube tends to drop down slightly because of the lack of supporting vertical flows. Stream tube 1 absorbs the momentum from the vertical flows, moves past the lights, then goes back to the supply wall forming a horizontal loop close to the ceiling, then moves through the surgical field in a crooked path and exits straight through the exhaust opening. Stream tube 2 moves in a simple path around the lights then goes down and exits straight. Stream tube 3 falls strongly since there is no supporting vertical flow far away from the central region, and then dies out without exiting the room.

Chapter 8

Discussion

8.1 Stream Line Comparison

- For Case 1, first of all we get the laminar flow, then turbulent flow is created & some vortex also created.
- For case 2, laminar flow is created for a little time, then a transition & later on turbulent flow created.

8.2 Speed Comparison

- For Case 1, at the supply duct, the speed of air is max & at the exhaust it is also max. in the other place it is mostly constant.
- For case 2, at the supply duct, the speed of air is max & at the exhaust it is also max. in the other place it is mostly constant, beside the light, there is slight change of speed.

8.3 Pressure Comparison

- For Case 1, at the upper portion the pressure is maximum & gradually pressure is lowering.
- For case 2, at the upper portion the pressure is maximum & gradually pressure is lowering. But pressure layer is fluctuating at the middle because of destruction with the light & human.

8.4 Temperature comparison

- For Case 1, at the upper portion the temperature is maximum, because of the heat flux from the light & gradually temperature is lowering.
- For case 2, the temperature is maximum at the upper portion of the human body because of heat flux from human body.

8.5 Contaminant concentration Comparison

- For Case 1, Contaminant concentration is maximum at the upper portion of the patient, where the flow of contaminant is running. It is gradually decreasing at lower part.
- For case 2, here the contaminant concentration is mostly same as the case 1.

8.6 Relative humidity Comparison

- For Case 1, at the supply duct, the RH is maximum & mostly constant at the lower portion, where the patient is laying. It is lower at the upper portion.
- For case 2, at the supply duct, the RH is maximum & gradually decreases at the exhaust portion.

Chapter 9

Conclusions

Conclusion

This paper presents a thorough analysis of air velocity, pressure, temperature, and relative humidity distributions, and contaminant transport in an air-conditioned operating room. It is found that airflow pattern significantly affects the performance of both contaminant removal and thermal comfort. For a simple assessment of thermal comfort, the mean air speed and mean relative humidity can be taken over the entire space or only over the breathing zone without much difference. However, the mean temperature can vary significantly over different air volumes. It is best to take mean temperature over occupied zone or breathing zone since the condition is closer to the occupants. Simple assessment based on mean temperature shows that the horizontal location of the supply grilles has significant effects on thermal comfort while that of the exhaust grilles does not. The GLM approach confirms the strong effects of the horizontal location of the supply grilles on thermal comfort and also on contaminant removal. A comparison between different response models shows that the GLM models can be used to replace the interpolation for three-level experimental design in most cases and that the interpolation for two-level experimental data shows a reasonably good agreement with the other models when there are only linear effects. For an overall design, considering the performance of the room on both contaminant removal and thermal comfort, it can be concluded that the closer the supply grilles to the center of the room, the better the performance is.

\

Appendix I

List of Figures

Appendix II

References

[1] AIA, AIA Guidelines for Design and Construction of Hospitals and Health Care Facilities, The American Institute of Architects, Washington, DC, 2001.

[2] ASHRAE, ASHRAE Handbook: Applications, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2003.

[3] J.E. Woods, D.T. Brayman, R.W. Rasmussen, P.E. Reynolds, G.M. Montag, Ventilation requirements in hospital operating rooms. Part I: Control of airborne particles, ASHRAE Transactions 92 (2) (1986) 396–426.

[4] J.R. Lewis, Operating room air distribution effectiveness, ASHRAE Transactions 99 (2) (1993) 1191–1199.

[5] F. Memarzadeh, Methodology for minimizing risk from airborne organisms in hospital isolation rooms, ASHRAE Transactions 106 (2) (2000) 731–742.

[6] F. Memarzadeh, A. Manning, Reducing risks of surgery, ASHRAE Journal 45 (2) (2003) 28–33.

[7] R. Mora, M. English, A. Athienitis, Assessment of thermal comfort during surgical operations, ASHRAE Transactions 107 (1) (2001) 52–62.

[8] P.O. Fanger, Thermal Comfort: Analysis and Applications in Environmental Engineering, McGraw-Hill, New York, 1970.

[9] C.A. Balaras, E. Dascalaki, A.A. Argiriou, A. Gaglia, HVAC systems and indoor conditions in Hellenic hospital operating rooms, ASHRAE Transactions 108 (2) (2002) 23–38.

[10] R. Kameel, E.E. Khalil, Energy efficient and hygienic operating theatres’ HVAC airside design architectural and engineering consideration, in: Proceedings of First International Energy Conversion Engineering Conference, Portsmouth, VA, 2003, AIAA 2003-5997.

[11] E.E. Khalil, R. Kameel, Requirements of air-conditioning systems' developments in hospitals and critical healthcare facilities, in: Proceedings of the Seventh Biennial Conference on Engineering Systems Design and Analysis, vol. 3, 2004, pp. 375–381.

[12] F. Memarzadeh, A. Manning, Thermal comfort, uniformity, and ventilation effectiveness in patient rooms: performance assessment using ventilation indices, ASHRAE Transactions 106 (2) (2000) 748–761.

[13] D.J. Hirnikel, P.J. Lipowicz, R.W. Lau, Predicting contaminant removal effectiveness of three air distribution systems by CFD modeling, ASHRAE Transactions 108 (1) (2002) 350-359.

[14] F. Memarzadeh, A. Manning, Comparison of operating room ventilation systems in protection of the surgical site, ASHRAE Transactions 108 (2) (2002) 3–15.

[15] R. Kameel, Assessment of airflow characteristics in air-conditioned spaces using 3D time-dependent CFD model, in: Proceedings of First International Energy Conversion Engineering Conference, Portsmouth, VA, 2003, AIAA 2003- 5960.

[16] T.T. Chow, X.Y. Yang, Performance of ventilation system in a nonstandard operating room, Building and Environment 38 (12) (2003) 1401–1411.

[17] B. Jayaraman, A.H. Kristoffersen, E.U. Finlayson, A.J. Gadgil, CFD investigation of room ventilation for improved operation of a downdraft table – novel concepts, Journal of Occupational and Environmental Hygiene 3 (11) (2006) 583–591.

[18] C.G. Helmis, J. Tzoutzas, H.A. Flocas, C.H. Halios, O.I. Stathopoulou, V.D. Assimakopoulos, V. Panis, M. Apostolatou, G. Sgouros, E. Adam, Indoor air quality in a dentistry clinic, Science of the Total Environment 377 (2–3) (2007) 349–365.

[19] Z. Rui, T. Guangbei, L. Jihong, Study on biological contaminant control strategies under different ventilation models in hospital operating room, Building and Environment 43 (5) (2008) 793–803.

[20] W.M. Kays, M.E. Crawford, B. Weigand, Convective Heat and Mass Transfer, fourth ed., McGraw-Hill, New York, 2005.

[21] ASHRAE, ASHRAE Handbook: Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2005.

[22] ANSI/ASHRAE Standard 55-2004: Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air- Conditioning Engineers, Inc., Atlanta, GA, 2004.

[23] ANSI/ASHRAE Standard 62.1-2004: Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 2004.

[24] StatSoft, Electronic Statistics Textbook, StatSoft, Inc., Tulsa, OK, 2006. Available from: <http://www.statsoft.com/textbook/stathome.html>.

[25] G.E.P. Box, J.S. Hunter, W.J. Hunter, Statistics for Experimenters: Design, Innovation, and Discovery, second ed., John Wiley & Sons, Inc., Hoboken, NJ, 2005.

[26] Fluent, Inc., FIDAP, CFD Analysis Software, 2005. Available from: <http://www.fluent.com/>.

[27] Fluent, Inc., GAMBIT, Mesh Generation Software, 2006. Available from: <http://www.fluent.com/>.

[28] C.A.J. Fletcher, Computational Galerkin Methods, Springer-Verlag, New York, 1984.

[29] S.R. Searle, Linear Models, John Wiley & Sons, Inc., Hoboken, NJ, 1971.