Applied Thermal Engineering 29 (2009) 2080–2092

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Three-dimensional analysis for hospital operating room thermal comfort and contaminant removal

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ARTICLE INFO

Article history:
Received 8 October 2006
Accepted 30 October 2008
Available online 13 November 2008

Keywords:
Computational fluid dynamics
Air conditioning
Ventilation
Predicted mean vote
Indoor air quality

ABSTRACT

This paper presents a three-dimensional analysis for thermal comfort and contaminant removal in a hospital operating room. The room 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, relative humidity, and contaminant concentration are presented and discussed. The simulation results show a good agreement with experimental data from the literature. 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.

1. Introduction

Health care facilities, machine shops, manufacturing and chemical processing facilities, and other commercial occupancies require ventilation and air conditioning for thermal comfort as well as for the removal of contaminants and other pollutions. A good design of ventilation and air conditioning provides a healthy and comfortable environment for people such as patients, workers, and visitors. 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 design of a heating, ventilating, and air-conditioning (HVAC) system for an operating room 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. 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 [1]. From HVAC design point of view, ASHRAE Applications Handbook [2] 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.

A number of experimental studies have been presented about infections and related factors in operating rooms. Woods et al. [3] 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 [4] 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

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1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2008.10.016

Nomenclature

C	mean contaminant concentration, kg/kg air
c_p	specific heat of air, J/(kg K)
D	mass diffusivity of species in air, m^2/s
f_{cl}	ratio of clothed surface area to nude surface area
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, $W/(m^2 K)$
I	thermal resistance in "clo" units, clo (1 clo = 0.155 m^2 K/W)
k	thermal conductivity of air, W/(m K)
K	regression coefficients (with subscript), m^{-1}
M	metabolic heat generation flux, W/m^2 of naked body area
p	pressure; partial pressure (with subscript), Pa
R	thermal resistance, m^2 K/W
T	temperature; mean temperature (with subscript), °C
u	velocity, m/s
v	mean air speed relative to the body, m/s
W	external work, W/m^2 of naked body area
Y	location of center of grilles
Z	performance response on thermal comfort or contaminant removal

Greek letters

β	thermal expansion coefficient, K^{-1}
ϕ	relative humidity
μ	viscosity of air, kg/(m s)
ρ	density of air, kg/m^3
ω	concentration of species, kg of species/kg of mixture

Subscripts

a	air
BZ	breathing zone
conv	convective
cl	clothing
E	exhaust
c	contaminant gas
r	radiant
ref	reference
S	supply
s	saturated
w	water vapor
w/a	water vapor in air (diffusivity of)
c/a	contaminant gas in air (diffusivity of)

consequences or results in a higher cost of treatment. Memarzadeh [5] 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 [6] 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. [7] studied thermal comfort in operating rooms. The thermal environment was studied in two operating rooms in a hospital. Thermal comfort was estimated based on the model proposed by Fanger [8] 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. [9] 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 [10] proposed a guidance to architectural and mechanical engineering designers to optimize the comfort and hygiene conditions in operating theatres. Later, Khalil and Kameel [11] 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.

The increasing developments of computational fluids dynamics (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 [12] studied the performance of a ventilation system in a typical patient room using CFD modeling. They were able to predict the necessity of using baseboard heating in extreme weather conditions. Also the validation of various supply air diffuser models gave useful guidelines on CFD modeling. Hirnikel et al. [13] 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 [14] 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 squame, or skin scale, around 10 μm 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 [15] 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 [16] 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. [17] 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. [18] 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