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CO_2-dispersion studies in an operation theatre under transient conditions

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Abstract

Maintaining air quality and thermal comfort inside an operation theatre equipped with horizontal jet flow type air-conditioning units, has been a challenge to engineers. The objective of this study is to analyze the airflow pattern in such operation theatres and the influence of location of the air-conditioners. The outcome of this study is expected to reduce the post-operation problems faced due to excess concentration of contaminants. Experimental studies were conducted in 10 different hospital operation theatres. Parameters such as air temperature and carbondioxide concentration were measured at discrete points chosen in the theatre. A 3D time-dependent numerical model was developed to simulate the airflow in terms of parameters such as velocity, temperature and CO_2 distributions in an operation theatre under transient conditions. The Eulerian approach using the volume fraction of the mixture of air and CO_2 was used to solve the numerical model. Finite volume approach was attempted in this work with PISO (pressure implicit with split operators) algorithm for the pressure correction equations. The simulated results were compared with the experimental results for validity. The locations of the air-conditioners were changed in the numerical model to analyze the airflow patterns and the contaminant distribution.

Keywords: Operation theatres; Airflow patterns; CO_2-dispersion; CFD; PISO and transient conditions

1. Introduction

Indoor air quality is a critical factor in the design of any hospital operation theatre. Studies of operating room air distribution indicate that the supply of air from the ceiling, with a downward flow movement to several ports located on opposite wall yielded probably, the most effective airflow pattern, maintaining the concentration of contaminants to a minimum acceptable level [1]. On account of ease of handling and economic considerations, window type air-conditioning units are used in many operation theatres. Window type units produce horizontal jet flow in contrast to the conventional downward flows. Simulation of airflow patterns for different locations of the air-conditioning units using computational fluid dynamics techniques help in analyzing air quality and thermal comfort. The variation in contaminant distribution, location of dead zones and air velocity in the operation theatre are the major factors that indicate the occurrence of post-operative wound infections.

Major contaminants in any hospital operation theatre are categorized as biological (microorganisms—fungi, bacteria and virus), chemical (waste anesthetic gases, CO_2, etc.) and particulate matter [2]. Microorganisms are the major cause for 'post-operative wound infections'. There are three main sources of contaminants: (a) the supply air to the theatre, (b) the surgical team members, and (c) the emissions of body vapors and organisms from the pathogens, these sources on mixing with the supply air gets deposited on the patient cause infections. The contaminants such as waste anesthetic gases and carbon dioxide, if not controlled properly can lead to severe complications. Most of the studies in the literature focus on air diffusion and solid contaminant behavior in indoor environments using CFD based integrated approach [3]. Studies on the distribution of CO_2 in the operation theatres have not been reported in the literature. An attempt is made here to study the CO_2 dispersion in an operation theatre using which the air quality is analyzed.

2. Indoor air quality in operation theatres

CO_2 concentration has been widely used as an indicator of indoor air quality. A Limit of 1000 ppm of CO_2 is

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Nomenclature

C_μ constant used in turbulence (k–ε) model, $C_\mu = 0.09$
CO_2 carbon dioxide (ppm—parts per million)
H_{room} height of the room (m)
K turbulent kinetic energy ($m^2\ s^{-2}$)
$l = 0.07L$

l is the characteristic length at the inlet (m)
Q_{EAS} quality of grid cells by Equi-Angle Skew technique
S source or sink
t' non-dimensional time-step (s)
T_I turbulent intensity (%)
U_{inlet} the inlet velocity ($m\ s^{-1}$)
V velocity vector
$v_{dr,p}$ drift velocity of the primary phase ($m\ s^{-1}$)
v_m mass averaged velocity ($m\ s^{-1}$)

Greek letters
α_p volume fraction of the primary phase
Γ_ϕ exchange coefficient (laminar + turbulent)
ε turbulence dissipation rate ($m^2\ s^{-3}$)
θ_{eq} characteristic angle corresponding to an equilateral cell of similar form
θ_{max} maximum angle between the edges of the element in degrees
θ_{min} minimum angle between the edges of the element in degrees
ϕ dependent variable
ρ density ($kg\ m^{-3}$)
ρ_p density of the primary phase ($kg\ m^{-3}$)

recommended to satisfy comfort criteria and CO_2 concentration is also an useful indicator of insufficient outside air intake and ventilation problems [22]. In this study CO_2-dispersion is used in predicting the regions of high contamination in the operation theatre. The patients in hospital isolation rooms constantly produce transmissible air-borne organisms by coughing, sneezing or talking, which if not under control, results in spreading air-borne infection. The air supply to the operation theatre should normally be free from such air-borne infectious sources. CO_2 being a common gas and a basic indicator of air quality, is used for simulation studies, the numerical model developed can also be used for the simulation of any other waste anesthetic gas in theatres. Hypercapnia is a condition that is abnormally caused by shallow respiration or hypoventilation. It is an excessive amount of CO_2 in the blood. Very high concentrations of atmospheric CO_2 results in hypercapnia [7].

Studies have shown that there are numerous health effects associated with the exposure of waste anesthetic gases [4]. These include increased risk of spontaneous abortion in females exposed to anesthetic gases in hospitals with incidences of 1.5–2 times greater than in unexposed females. The prevention of post-operative infection is dependent on several factors including effective sterilization and disinfection procedures, good surgical technique, theatre design, bacterial contamination of theatre air, discipline—which include restricting the movement of staff near the operating table, appropriate use of prophylactic antibiotics, etc. [5].

It has been found that velocities as high as 0.6 $m\ s^{-1}$ are unsatisfactory because the exposed internal tissues of the patient are over-cooled and dried out by evaporation [6]. Parameters such as air temperature and humidity also play a vital role in surgeries. If the operation room temperature is higher during the eye surgeries, then the cornea dries out and laser beam removes more corneal tissue and an over-correction can result. The reverse occurs if the temperature in the operating theatre is too low. If the humidity is higher than the cornea is wetter and the laser removes less tissue with each pulse, increasing the chance of an under-correction [8]. These factors prove the need for the study and its significance.

2.1. Operation theatre indoor airflow and contaminant distribution simulation

Airflow simulation using CFD techniques is an useful tool to analyze air movements in non-standard operating room situations [9]. Modern computational fluid dynamics models are used to predict the air velocity, temperature, turbulence level and contaminant distributions. The current work uses a transient model based on eulerian approach for simulation of indoor airflow and contaminant distribution.

In 1997, Lo [16] has made a study addressing contamination control in an operating room. The study considered an operating room under isothermal condition and analyzed the distribution of contaminants. In a first assumption made in the study, the effect of significant thermal plumes in the room was ignored. In a second assumption it was considered that the particles in the room can be considered to follow Brownian motion. These assumptions were reconsidered by Memarzadeh and Manning [18] in their study conducted in reducing the risks in surgery. The basic assumption made in their study was that the squames were simulated as particles being released from several sources surrounding the occupant. These particles were then tracked for a certain period of time. The Brownian motion is strictly applicable to particles that are 1 μm or less in diameter. Bacteria and virus do conform to this criteria but bacteria are usually transported in operating rooms by squames [17], which are considerably bigger (in the range of 10 μm) and so do not necessarily follow Brownian motion. Numerous studies on the simulation of particle trajectories in rooms are reported in the literature but much little is focused on the of gas dispersion, hence this study.

Studies conducted on airflow regimes in air-conditioned operating theatres suggest that the supply of air from the ceiling, with a downward flow movement to several exhaust ports located on opposite walls yielded, probably the most effective airflow patterns maintaining the contaminant concentrations to a minimum acceptable level [10–12]. In contrast this study focuses on the window type air-conditioning units, which are used on account of ease of handling and economic considerations. The window type models have a major