OPTIMIZATION OF AIRFLOW REGIMES, ENERGY EFFICIENCY, AND AIR QUALITY IN SURGICAL OPERATING THEATRES

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ABSTRACT

The present paper addresses and fosters the factors that affect airflow movement and energy efficiencies in the surgical operating theatres. The present work puts forward analyses for major factors con tributing to failure to achieve and attain the optimum Indoor Air Quality (IAQ), and the methods suggested to solve such problem. Appropriate architectural and mechanical engineering recommendations to achieve the optimum hygienic operating theatre are set out in the paper. The present work is also devoted to assess through way of comparisons of several airside HVAC designs, efficient operating theatres air conditioning designs. The influence of the airside HVAC design on the operating theatre environment is outlined in terms of flow regimes, and age of contamination.

INTRODUCTION

In the last decades, the more complexity of architectural designs and less area available for equipment, rendered the selection and design of HVAC airside systems a great challeng e. The attainment of comfort conditions was the target of the HVAC engineers and designers since the late of fifties of twentieth century. The sixties of last century marked the beginning of the introduction of new hygiene conditions in the healthcare appl ications with the aid of ventilation systems, especially in the surgical operating theatres. Charnley published several researches regarding the optimum sterile conditions in the surgical operating theatres; he also introduced the concept of the “Clean Roo m”, which was called later the “Charnley Chamber”, as an ultimate design figure in clean operating rooms (Charnley 1964, 1972).

In the early sixties, the airflow and thermal comfort parameters were considered as the key components to attain optimum IAQ in the operating theatres. Many investigations evaluated the airside performance of the HVAC systems in operating theatres. These investigations compared the HVAC system performance through numerous suggested approaches to provide a measure of the IAQ. Actually, the HVAC system parameters play an important role in the healthcare applications. Actually, the air distribution performance was comprehensively investigated in fewer investigations and some of these emphasized the importance of airflow distribution on the IAQ level in healthcare applications. The international societies developed several standards to deal with the airside designs of the surgical operating theatres.

In 1960, Blowers and Crew published the results of their attempts to define principle s in design of ventilation systems for operating theatres. They undertook field studies in 25 operating theatre suites, ten of which had extract ventilation only, in different parts of Britain. Utilizing a full-size dummy theatre with Bacillus globigii spo res as markers of airflow, they examined the effects of various patterns of distribution and rate of air input from six ceiling apertures. The authors made their recommendations, including simple filtration of input air (no more than 99.9% efficiency for 5μ particles), adjusting air pressure gradients to enforce airflow from cleaner to dirtier zones in the operating theatre suite. Hence they had dispensed with exhaust ports in plenum ventilated theatres in favour of pressure-relief flap valves in order to r educe the volume of input air required to maintain positive pressure. The relative merits of turbulent and downward displacement ventilation were discussed and it was concluded that the balance of evidences was in favour of the latter but there was little advantage in exceeding a rate of air input of 1200 cu ft/min (17-20 changes/hour). In the same year, (Lidwell et al., 1960) assessed the behavior of different theatre ventilation installations using a gaseous tracer (nitrous oxide) and noted that there were no absolute standards for permissible levels of contamination. They advocated that specifications for air input should be expressed in terms of the volume of air supplied rather than the rate of air change. It is interesting to note however, that the latter terminology has survived to the present day.

At 1960, (Greene et al., 1960), were the first to perform an investigation concerned with the design of air conditioning system to reduce the infection. They focused on the importance of optimum selection to air handling systems that would provide air movement patterns that minimizes the spread of contamination. They measured the airborne bacterial count in different places in the hospital to get the effect of the airflow on those counts. No details about the optimum airflow pattern were presented. (Michaelson et al., 1966) introduced the laminar airflow concept for the first time; they introduced that concept without any advice about the way of reaches that flow, or the suggested procedures. At 1981, Pfost reevaluated the concept of laminar airflow in the operating theatres that proposed by (Michaelson et al., 1966). Pfost advocated the downward movement as the most effective air movement pattern for maintaining the concentration of contamination at an acceptable level. The investigation of (Pfost, 1981) was seen to be the first work that was concerned with the airflow patterns and direction in the surgical operating theaters. Pfost introduced several types of the sir supply positioning in the ceiling to reach the most probable situation. The completely perforated ceiling was claimed as optimum solution for the air conditioning inside the surgical suites. Pfost suggested also the necessarily to extract air near the floor to maintain the downward flow.

Since that time, many other researches reported other techniques to prevent the infections in the operating theatres. Those techniques present and put forward some more additional restrictions on the HVAC systems, such as incorporating types of air filters and use of ultraviolet technique in killing the bacteria.

Interest in the use of Ultraclean Air Ventilation (UCV) systems in operating theatres in the UK dated back to the 1960s at a time when increasing numbers of hip replacement operations were being performed. The history of the clean air systems used by Charnley in his hip surgery unit is documented in a series of papers published in the 1960s and 70s. In 1970, Scott described laminar/linear flow ventilation and its application to surgery and indicated that these systems had been in use in operating rooms in the USA for three years at the time of writing. Others expressed doubts about this type of ventilation in general surgery (Shaw et al., 1973). (Whyte et al., 1971) reported on an experimental laminar flow system with optional down or cross-flow of HEPA-filtered air with variable velocity that had been installed in an orthopaedic unit near. They published their bacteriological evaluation and concluded that the downflow system was bacteriologically superior to crossflow.

The results published by (Lidwell et al., 1982) had concluded that ultraclean air in operating rooms reduced the incidence of "deep sepsis" after total joint-replacement operations and that this reduction was enhanced when the operating team wore whole-body exhaust suits. (Whyte et al., 1982) had also compared Ultra Clean Ventilation systems and the conventionally ventilated theatres for large joint replacement surgery and found that UCV resulted in a 97 fold reduction in bacterial air counts and a 35 fold reduction in wound washout bacterial counts. They calculated that 98% of the bacteria recovered from the wound of a joint replacement operation performed in a conventionally-ventilated theatre came from the theatre air, the majority indirectly, i.e. after deposition on surgical instruments etc exposed to the air. Similar conclusions were reached by (Lidwell et al., 1983). In 1983 (Whyte et al., 1983) proposed bacteriological and other standards for UCV theatres and these were taken up by a DHSS report in 1986.

(Isoard et al., 1980) and (Luciano, 1984) confirmed that the advantage of their techniques was to primary decreases infection rates; some disadvantages of laminar flow techniques are space restrictions, noise, and cost. Some disadvantages to ultraviolet radiation are the inconvenience of dressing for protection, potential for eye irritation, and erythema.

Those new techniques were examined and the outcome standards had given additional restrictions on the proper airflow direction depending on the later investigations. (Bhattacharyya, 2000) found that in operating rooms, airflow should be directed away from the patient and advised the designers to consider the importance of the air distribution; the positioning of air supply outlets, air exhaust ports, and partial walls as useful design elements to maintain the air environment in the surgical operating theatre. (Gurry, 2000) recommended that the airborne bacteria in an operating room might not be eliminated even by providing "bacteria free" air from the air handlers, else if using directional and free turbulence airflow. It was also found that turbulence could stir up the previously settled particles on horizontal surfaces. The causes of turbulence in the operating room were referred to the improper positioning of supply diffusers, exhaust grills, opening of doors, blocking of exhaust grills by equipment, circulation of operating room personnel, etc.

Those recommendations can be summarized as follows: the ventilating air is to be supplied from ceiling or high on the walls in each room, and the supplied air should then be exhausted from several inlets located near the floor on opposite walls. All of those have been carried out in attempt to reach to the status of "Charnley Chamber".

(Moscato et al., 2000) introduced a geostatistical method to assess spatial distribution of anaesthetic gases in the operating theatres and hospital staff exposure to promote risk management. In their investigation, they found that the critical factors for the air quality is the efficacy of the air conditioning and filtration system. It was stated that the evaluation of the air conditioning plant efficacy could not be achieved only on the basis of the number of air exchanges, which does not take into account the real route of the air in the room. (Streifel, 2000) discussed the importance of ventilation systems to insure an optimum infection control. It was stated that both the air distribution and direction play the more important role in the airborne-infectious-disease management; good IAQ starts with building design.

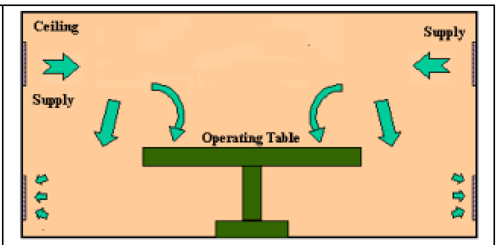
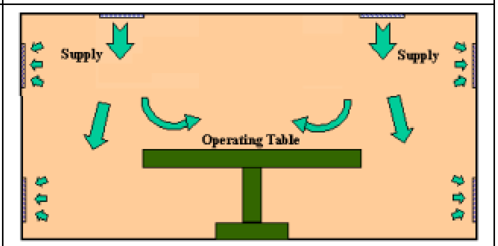
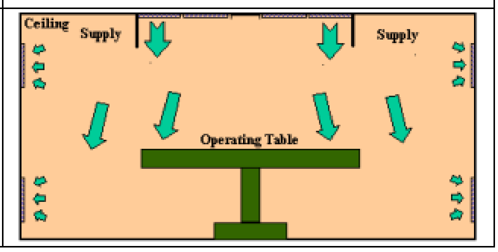
(Chow et al., 2000) simulated their operating theatre using CFD model. They investigated the velocity distribution and air age using the Re-Normalization Group (RNG) k-ε model. They performed field measurements to record the air velocities at operating theatre boundaries. They found that the re-circulating flow rate is only 56% of the supply airflow rate; so there was much room to make the system more energy efficient. The sophistication of HVAC systems in healthcare premises is necessarily increasing. Optimum supply air-distribution systems provide the required effects within the surgical field rather than in the entire room. The air movement as a whole will ultimately depend on the supply air velocity, velocity profile, the provision of full or partial partition walls, the locations of the supply/extract grilles, and the supply/room air temperature difference. Uncontrolled short-circuiting should be avoided.
(Chow et al., 2000) reported that airflow simulation models are useful tools to analyze air movements in non-standard operating room situations. The use of the correct discharge velocity at the supply diffuser is important for efficient system operation. Ultra-clean ventilation (UCV) systems are designed and commissioned in accordance with the guidelines that provide significant benefit and confidence to the resulting airflow pattern, turbulence levels and comfort. Therefore, some stringent requirements should be imposed to protect the users.

Purpose of the Present Work
This paper is concerned with the investigation of the influence of the surgical operating theatre airside design on the efficiency of the HVAC airflow to create sterile conditions in the theatre. The present work is devoted to investigate the relation between airflow improvement and the operating room airside designs and introduces three airside designs most commonly used around the world. The three designs are compared together to indicate the influence of the airside design on the IAQ level. The airflow velocity and local mean age will be used as indicator of the analysis.

PROPOSED AIRSIDE DESIGNS

The commonly known three different airside designs depend mainly on the available architectural designs and the flexibility of those designs. Indeed, two of those designs are applied on the most of hospital around the world. The third design is proposed here to overcome the problems of the other two designs. The three designs are illustrated as shown in Table 1. For the vertically downward flow the upper level of extraction is proposed.

Table 1 Proposed airside designs

Design A Horizontal supply	
Design B Multi ceiling supplies	
Design C One Central Supply	

MATHEMATICAL SIMULATION

Three time-averaged velocity components in X, Y, and Z coordinate directions were obtained by solving the governing equations using a "SIMPLE Numerical Algorithm" [Semi Implicit Method for Pressure Linked Equation] described earlier in the work (Spalding et al., 1974), (Launder et al., 1974), (Khalil, 1978). The turbulence characteristics were represented by a modified and appropriately extended two-equation k - ε model to account for normal and shear stresses and near-wall functions. Fluid properties such as densities, viscosity and thermal conductivity were obtained from references. The present work made use of the Computer Program 3DHVAC, which was developed, by (Khalil, 1999) and modified later by (Kameel, 2002), and by (Kameel, 2002). The program solves the differential equations governing the transport of mass, three momentum components, energy, contaminant concentration in three-dimensional configurations.

Numerical Procedure

The solution of the governing equations can be realized through the specifications of appropriate boundary conditions. The values of velocity, temperature, kinetic energy, and its dissipation rate are specified at all boundaries.

The numerical solution grid divided the space of the surgical operating theatre into discritized computational cells (80 x 60 x 30 grid nodes) using the modified hyperbolic equation of (Kameel et al., 2002). Solution convergence criteria, was applied at each iteration and ensured the summations of normalized residuals were less than 0.1% for flow, 1% for k and ε, and 0.1 for energy.

Model Validation

Previous comparisons between measured and predicted flow pattern, turbulence characteristics, and heat transfer were reported earlier in the open literature utilizing the present computational capabilities (3DHVAC), reference should be made to these for further details and assessments. A summary of the main assessment is expressed here as follows. The predictions of flow and turbulence characteristics are in general qualitative agreement with the corresponding experiments and numerical simulations published by others, (Blum, 1956), (Neilsen, 1989) as indicated in the work of (Kameel 2002). General trendwise agreements were shown and trends are in adequate agreement for engineering purposes. Nevertheless discrepancies exist and particularly in the vicinity of recirculation zone boundaries. More discrepancies were also observed in heating flow situations than those of ventilation or cooling. The work of (Kameel, 2002) and (Kameel et al., 2003) described the validation of the turbulence model to use it for the prediction of airflow characteristics in the surgical operating theatres and introduced a complete case study performed in a 1200 bed teaching hospital (New Kasr El-Aini Teaching Hospital, Cairo University).

RESULTS

One can be divide the operating theatre domain into two areas, clean area and contaminant area. Indeed, the clean area is not perfectly pure from any contaminant but it is acceptable as clean area within permissible range of existing contaminants. The clean areas are those areas, which are directly supplied by the clean and fresh air, which has the lowest local mean age. Actually, it is required to provide the clean air to the operating zone continuously. The operating zone is the most important zone in the theatre.

The design 'A' is a horizontal airflow configuration from the sidewalls and the air is extracted from ports near to floor. This design provides poor airflow over the operating table and correspondingly poorer scavenging, which decreased the hygiene level, but also, expensed the most of the conditioned air (paid for air) by throwing it without any useful utilization. Most of the supplied air is extracted directly from the extract ports due to the air short circuit, Figure 1. The results of the local mean age of air from the present simulation indicated that the older air is concentrated over the operating table, Figure 2. Indeed, this design does not provide the energy efficient solution as air is being short-circuited directly to exhaust ports. The poor distribution of the supply outlets and the extract ports contributed to this problem.
The architectural design restrictions may force such design on the most of HVAC designers particulary for low ceiling height rooms. These architectural restrictions could be summarized in the following:

- Unsuitable operating room height, which prevents the HVAC designer to use the false ceilings.
- The restriction to use the other walls for extract ports.

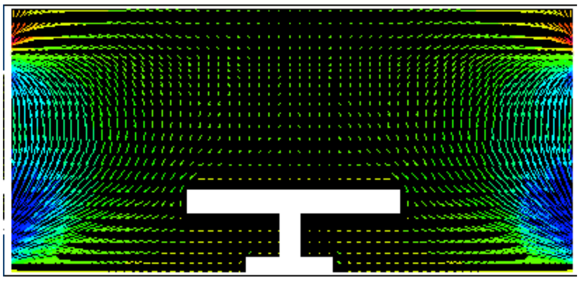


Figure 1 Airflow distribution of design 'A'

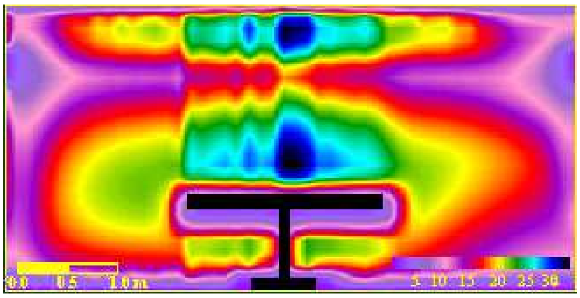


Figure 2 Local Mean Age distribution of design 'A'

On the other hand, Figures 3 and 4, indicated the velocity vectors and air mean age for the proposed design 'B'. It can be seen that these flow pattern do not provide any optimum clean occupancy area nor an in the rest of the room. The proposed design 'B' is completely unaccepted design model and should not be recommended for design implementations.
In performing the three comparison cases, the same Air Changes per Hour ACH, were used, hence the

supply air velocity in the case 'A' is larger than the corresponding velocity of design 'C', which had larger face area. That leads to decrease the maximum Local Mean Age LMA value of design 'A' than the corresponding value of design 'C', as indicated in Figures 5 and 6. The unacceptable values of LMA are concentrated over the operating table. The LMA values in the vicinity of the extract ports were found to be less than the corresponding LMA values in the vicinity of the operating table, this indicates increased contaminant concentration in the vicinity of operating zone.

The proper description of the designs 'A' and 'B' are 'Inefficient Sick Design'. On the other hand the proposed design 'C' gave a perfect protection in the vicinity of the operating table and created the proper conditions in the operating area as a whole.

The architectural design restrictions may force the design 'B', to be used by HVAC designers. The restrictions of the architectural and civil engineer to use a large area in the center of the room as a supply outlet

The upper extract level is recommended in the desi gn 'B' to reduce the backward flow near the sidewalls. The architectural and civil engineering designers should provide a suitable sound design of the surgical operating theatres to enable the HVAC designer to use the design 'C', which provides clean area over the operating table.

CONCLUSIONS

The previous investigations of airside designs and previous researches of energy efficiency and IAQ performance had clearly indicated that we should efficiently utilize energy to obtain the comfortable and hygiene design.

The cross or horizontal flow, as the present proposed design 'A', was found to result in what is termed as inefficient sick design. On the other hand, the downward flow pattern developed by separate individual ceiling supply diffusers, design 'B', doesn't adequately furnish the functionality of the downward flow for providing sterile environment in the operating area.

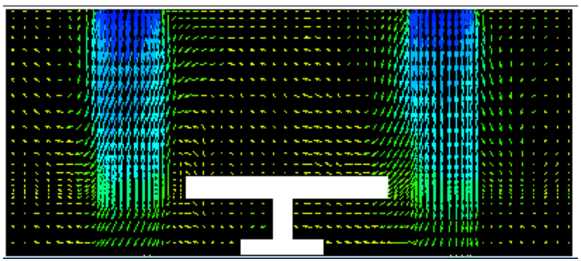


Figure 3 Airflow distribution of design 'B'

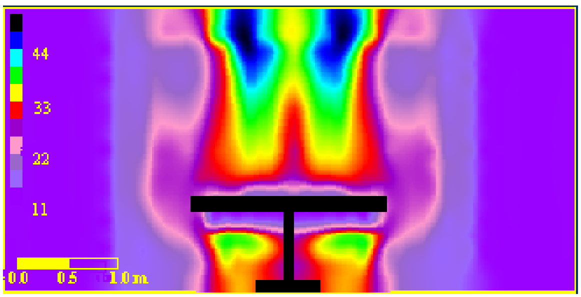


Figure 4 Local Mean Age distribution of design 'B'

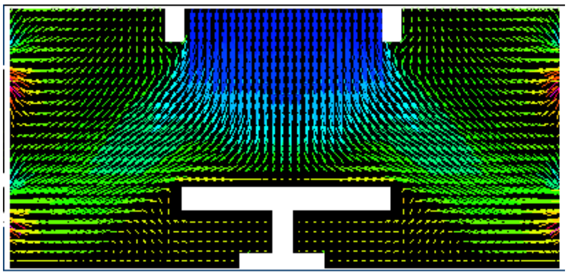


Figure 5 Airflow distribution of design 'C'

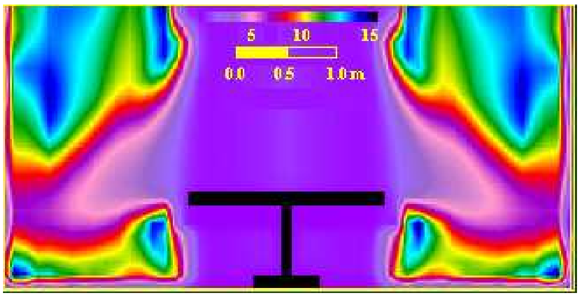


Figure 6 Local Mean Age distribution of design 'C'

DISCUSSIONS AND RESULT ANALYSIS

The above results had indicated the effect of the airside design on the IAQ and energy consumption inside the surgical operating theatres. The cleanest area in the room is the area in the vicinity of the supply outlets. The HVAC system designer should prevent the contaminant transfer to this cleaner area.

Incorporating central ceiling supply plenum with perforated diffusers over the operating area; design 'C', provides an appropriate solution for the complex situation of healthcare application by providing acceptable IAQ level in the operating zone with proper thermal comfort and flow pattern. In contrast to many of previous researchers considering air as the medium of infection sources, the paper, considered the air as the working media, in th e hands of HVAC designers' to prevent infection inside the operating theatres. The proper design of the airside system enhances the airflow distribution in the healthcare domain and provides energy efficient solutions.

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