Experimental Investigation of Flow Regimes in An Operating Theatre of 1200-Beds Teaching Hospital

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Optimum design of air condition in surgical operating theatres requires more careful and refined control of flow and temperature characteristics to achieve sterile and comfort conditions. The present work is devoted to analyze the performance of HVAC system design in practical operating theatre in 1200-beds of Egyptian modern teaching hospital. The present experimental program comprises field measurements of air velocity, and temperature, in the vicinity of supply air diffusers and operating area. The obtained experimental results illustrate the distinct interaction of the HVAC system design parameters. The present work introduced some recommendations to ensure prevailing aseptic conditions and also demonstrated the effect of air conditioning system design on the temperature distribution the operating theatres.

I. Introduction

Modeling of airflow patterns and regimes in air-conditioned spaces enhances the understanding of the interactions between airflow, heat and mass transfer under various geometrical and operational conditions. In full-scale applications of large air-conditioned conference rooms, operating theatres, telephone exchanges, and information technology rooms, experimental investigations of all effective parameters would be expensive and time consuming. In designing, the appropriate airflow system inlet and outlets locations, sizes, and flow characteristics, optimization is ultimately needed to yield the best and most economical viable design. Designers need directive recommendations and guidelines; those are normally provided through codes, standards, and regulations\textsuperscript{120}. The ASHRAE handbooks, standards, and norms had aided such design procedures those broadly specifying guidelines.

The advent of three-dimensional modeling techniques, over the past few years had greatly aided the understanding of what happens in complex geometries. Over the past decades, literature had indicated comprehensive sets of flow and temperature measurements in large air-conditioned spaces. Those include, but not limited to, the work of Blum\textsuperscript{2}, Hosni et al\textsuperscript{4}, Medhat\textsuperscript{18}, and Kameel et al\textsuperscript{6-9} and Kameel et al\textsuperscript{12} and Khalil\textsuperscript{16}. The measurements included time averaged velocity components and time averaged temperature under steady state conditions. Conventional measuring techniques were reported including pilot cylinders, tubes and spheres, heated thermocouple anemometers, hot-wire anemometers, etc. Temperatures, on the other hand, were measured with the aid of thermocouple based pro. Most of the previous work reported in the literature concentrated on flows away from supply and return vicinities, with more emphases on recirculation zone, forward flow and jet spread and drop. Reported experimental accuracies were ± 5 % for velocities and ± 2 % for temperatures. Studies of operating room air distribution equipment and careful installations of clean rooms indicated that the supply of the air from the ceiling, with a downward flow movement to several exhaust ports located on opposite walls yielded, probably, the most effective airflow pattern, maintaining the concentration of contamination to a minimum acceptable level. Completely perforated and partially perforated ceilings, and ceiling-mounted diffusers have been successfully utilized. Pfost\textsuperscript{20}. In general, outlets supplying air to sensitive ultraclean areas should be located on the ceiling, while exhaust outlets should be near the floor. The unidirectional laminar airflow pattern is commonly attained at velocity of 0.45 ± 0.10 m/s. Laminar airflow has shown satisfactory results for patient treatment rooms which may be highly susceptible to infection; such patients would include, those badly burnt, undergoing radiation therapy, concentrated chemotherapy, organ transplants, amputations, and joint replacement. The sophistication of HVAC systems requirements in healthcare premises is 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 walls, the locations of the supply/extract grilles, and the supply/room air temperature difference. Short-circuiting should be avoided, Chow et al.\textsuperscript{3}.

Airflow simulation is a useful tool to analyze air movements in non-standard operating room situations. The use of the correct discharge velocity at the supply diffuser is important for 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, Chow et al.\textsuperscript{3}. The present work is devoted to analyze in a more comprehensive manner what happens in the immediate vicinity of the supply jet outlet and return grilles, in addition to general flow field characteristics. The aim is to obtain a set of experimental airflow velocity and temperature profiles in the immediate vicinity of the air diffusers and grilles. These would be used as inlet initial conditions for the solution of the governing transport equations of mass, momentum, and energy in the complex geometries under investigation. Khalil\textsuperscript{13,16}, had indicated the significance of proper selection and specification of inlet and boundary conditions.

II. Experimental Investigations

The present work was carried out in an actual operating theatre at New Kasr El-Aini Teaching Hospital at Cairo University. The hospital comprises 1200 beds, 16 operating theatres plus four emergency wings. The HVAC system that serves the hospital under consideration is all air system (Variable air volume VAV). The HVAC System is in operation most of year. In new Kasr El-Aini teaching hospital, the air conditioning system of surgical operating theatres was designed as an all air system that supplies the different zones in the hospital by air that satisfied the healthcare recommendations according to ASHRAE standards. The air conditioning system operates on 100 % fresh air principle with airflow rate to room volume ensuring more than 15 air changes per hour. The room in question is 6.6 m in length, 4.0 m in width, and 3.0 m in height. Figure 1 shows the geometrical configuration of the operating theatre, it also indicates the location of supply and exhaust grilles and operating table with the illustration of layout sketch and a photo.

The air is supplied to the room through four square, (60 x 60 cm) , ceiling perforated diffusers located as shown in Figure 1; their centers were located at X, Y equal to (1.7,1.3) m , (4.9,1.3) m , (4.9,2.7) m , and (1.7,2.7) m . The extracted air was collected through two grilles at one wall, their centers, at two different heights of 0.75 m and 2.25 m from finished floor. The upper extract grille was 0.5 x 0.3 m while the lower had the dimensions of 0.5 x 0.2 m the supply air velocity at the supply diffusers were calculated as averaged value of 0.3 m/s while the velocity at the extract ports were averaged as 1.728 m/s , Kameel 2002. The supply grille side length Lo is 0.6 m while Wg and Lg denote the location of the measuring probe along the grille face as shown in Figure 1.

Measurements of the time averaged W velocity component in the Z direction were obtained with the aid of a thermal anemometry, Kameel and Khalil 2001, with an accuracy of ± 5 %. The measuring probe was supported on a three-dimensional versatile traversing mechanism that is capable of three-dimensional motion at 5 mm increments. The velocity probe diameter was 1 mm, which when related to room size occupancies is less than 2 x 10\(^{-9}\) % of the measuring domain. The temperature measurements were obtained with thermocouple probe housing arrangement supported to the three-dimensional traversing mechanism. The probe error analyses reported accuracy of ± 2 %.

III. Experimental Results

The obtained measurements were concentrated at three more important zones, namely
- Supply diffuser vicinity;
- Extract diffuser vicinity; and
- Operating table vicinity

The present work will represent more details about the velocity and measurements in the vicinity of the supply diffusers.

The operating table zone represents the local point of the actions in the theatre and where, laminar flow, with no turbulence and almost uniform temperature should be maintained. The obtained air flow velocity profiles at various distances downstream of the supply diffuser centered at (4.9,1.3) m are shown in Figure 2. The measurements indicated slightly asymmetrical profiles through the 64 measuring points at each measuring horizontal plane identified by Z/H = 0.933, and 0.9 measured from the room finished floor (H being the room height = 3 m). Figure 2 shows the measured velocity contours obtained at various locations; the observed slight asymmetrical behavior can be attributed to the effects of the lightingfixtures inducing heating effects, hence influencing the flow patterns. The figure also shows the corresponding predictions of Kameel and Khalil\textsuperscript{19}. Those predictions were obtained with the aid of a mathematical approach to numerically predict the flow regimes, heat transfer and relative humidity in surgical operating theatres of different internal loads. Full three-dimensional finite difference solver of the governing conservation equations of mass, momentum, energy, and contaminant age was utilized with the k-ε turbulence model closure. The numerical grid comprised 80x60x30 nodes that map the operating theatre domain with special wall treatment for inlets,outlets,operating table and walls,Kameel\textsuperscript{19}. Measured radial profiles of time-averaged air temperature are shown in Figure 3 at various locations downstream the supply diffuser. The profiles indicated uniform distribution across the jet in the immediate vicinity of the diffuser Z/H = 0.983. At further downstream locations, the local temperatures increased due to the heat exchange with the room and heat gains from the lighting fixtures.
Figure 1a. Practical Surgical Operating Theatre - Schematic Layout with photo and Measuring Locations.
The temperature profiles, measured in the vicinity of the same diffuser at corresponding locations, differ from each other by less than ±1%. It should be emphasized that due to the use of one-sided extract grilles wall, the general flow pattern in the room is predicted to exhibit asymmetrical behavior. The results shown here are the measured data at the diffuser vicinity that can well be used as outlet boundary conditions to numerical computations. Figure 4 presented a comparison between measured and predicted temperature contours at two different levels downstream the same supply diffuser configurations of Figure 2. Previous numerical investigations of the air flow patterns using four individual ceiling diffusers such as in Figure 1 versus the other technique using single central ceiling plenum of multiple diffusers are shown in Figures 5 & 6. Both designs are used in USA and UK respectively. It should be noted that these two figures were obtained in a vertical plane at y = 2.0 m.

The operating table zone is the critical area where minimum turbulence, minimum age should be present. Figure 5, for design with four individual supply diffusers 0.6x0.6 m each indicated small area that meets the criteria of smaller age, low turbulence and comfort thermal conditions. On the other hand, Figure 6 clearly indicated the existence of such criteria to a larger extent (White unshaded area). The influence of air distribution pattern is dramatic in affecting the characterization of Local Mean Age LMA distribution pattern. On the other hand the proposed design of Figure 6 resulted in the formation of refined protection in the vicinity of the operating table and created the favorable proper conditions in the operating area as a whole due to the persisting of large area that has less turbulence, let temperature and lower velocities (white colored areas).
Figure 2. Contours of Measured and Predicted W- Velocity Component at various levels downstream the ceiling diffuser level (various Z/H)
Figure 3 A. Measured Profiles of Temperatures in the Vicinity of the Air Supply Diffuser at various lateral positions $W_g/L_o$

Figure 3 B. Measured Profiles of Temperatures in the Vicinity of the Air Supply Diffuser various lateral positions $W_g/L_o$

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Figures 3 C. Measured Profiles of Temperatures in the Vicinity of the Air Supply Diffuser various lateral positions \( W_g/L_o \)

Figures 3 D. Measured Profiles of Temperatures in the Vicinity of the Air Supply Diffuser various lateral positions \( W_g/L_o \)
Figure 4. Measured and Predicted Contours of Air Temperatures at various levels downstream the ceiling diffuser level (various Z/H)
Figure 5. Predicted Contours of Air flow pattern, Temperature and turbulence using multiple ceiling diffusers, Kameel and Khalil [11] in X-Z Plane at Y=2.0 m.

Figure 6. Predicted Contours of Air flow pattern, Temperature and turbulence using single ceiling plenum, Kameel and Khalil [11] in X-Z Plane at Y=2.0 m.
IV. DISCUSSION AND CONCLUDING REMARKS

The present work shown here presents part of the full results obtained in the operating room investigations. In such complex flows, the obtained velocity profiles $W$ at various radial positions were obtained and indicated near-flat pattern across the individual supply diffusers. The velocity decays away from the grille into the room as shown in figures 3 and the diffuser centerline velocity decay are consistent with the corresponding jet expansion and diffusion. The jet spread and decay is characterized by the existence of a mushroom shape flow pattern with strong traverse momentum exchange up to the operating table upper surface. The results show the unsymmetrical distribution of the jet induced from the supply diffuser. The velocity in outer side of the diffuser relative the operating table is larger than the velocity near the inner side. This implicates the effect of the upward flow over operating table.

Previous predictions of flow pattern had indicated airflow dispersion to the side walls, with more inflow forward. The supply diffusers pronounced penetration of the supply jet, which forms a kind of down flow air curtain around the operating table. Figure 4 was added here for the sake of flow pattern clarification; the Figure presents the predicted $W$ velocity contours in an X-Z plane at $Y = 1.3$ m as reported by Kameel et al.\textsuperscript{6} and Khalil\textsuperscript{16, 17}. Investigation of the HVAC system in the operating room under consideration showed that the operating area is protected by the created air envelopes surrounding the table by the use of four diffusers. From results one can observe the effect of the upward (backward) flow over the operating area on the left side penetration of the diffuser jet.

The operating staff members have a significant and pronounced effect on air movement in the room. Persistent jet penetration was measured around the operating table. Such flow characteristics would be affected by the movement of the surgical team in and out of this zone. The microbial level in operating room air is directly proportional to the number of people moving about in the room, Ayliffe\textsuperscript{3} and in the present investigation; the movement will be across the protection-air envelope of the induced air curtain. So that HVAC system design should be modified to avoid such effect by changing the relative positions of supply diffusers relative to the operating table.

The following are the more important conclusions and findings of the present work

1. Measurements of mean $W$ velocity component (in the vertical $Z$ coordinate direction) were obtained in the vicinity of the ceiling square perforated diffusers. These are to be used as initial conditions in computational procedure to predict flow pattern and heat transfer characteristics downstream the supply diffusers in the room.
2. The corresponding measurements of mean air temperature profiles at diffuser outlet were also reported and are intended as inlet conditions to computational procedure.
3. The present HVAC design doesn’t provide a uniform air flow or thermal distributions for the entire space or in the comfort zone.
4. The present HVAC design results in the formation of large recirculation zones especially near ceiling. These recirculation zones get the air from the activity and operating area to throw in the vicinity of the supply fresh air that can decrease the whole effectiveness of the supply air to dilute the contamination existence.
5. The extract port location has a pronounced influence on whole comfort level on the healthcare application especially the surgical operating theatre. The distributed air extraction around the room surrounding can improve the performance of the air supply diffusers.

The most suitable design of HVAC systems in the surgical operating theatres should, consequently, follow the following recommended guidelines.

1. The supply air should be introduced from ceiling using several ceiling-mounted diffusers in a plenum (or complete perforated ceiling), to form a large supply area with low supply velocity. When several diffusers are incorporated, their relative position to the operating table should be carefully selected to provide the optimum protection.
2. Maintain the operating table away from the airflow direction, as much as possible, to decrease the turbulence level, and decrease the possibility of airborne bacterial flow creation or spread.

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