Building Simulation 2003

Eighth International IBPSA Conference
Eindhoven, Netherlands
August 11-14, 2003

ENERGY EFFICIENT THERMAL COMFORT VS AIR QUALITY IN AIR-CONDITIONED HEALTHCARE APPLICATIONS

Ramiz Kameel [1], Essam E. Khalil [2]
[1] Ph.D. of Mechanical Engineering
[2] Professor of Mechanical Engineering
Mechanical Power Engineering Department
Faculty of Engineering, Cairo University
Cairo, Egypt

ABSTRACT

The balance between the energy efficient thermal comfort and Indoor Air Quality (IAQ) in healthcare facilities is the main aim of this paper. The present paper will present this balance from the viewpoint of the air conditioning design. It was found that the design of the HVAC airside systems plays an important role for the energy consumption optimization and achieving the optimum IAQ. This paper highlights the importance of the proper airside design on the energy consumption, thermal comfort and IAQ. The present work introduces some recommendations for airside designs to facilitate the development of optimum HVAC systems.

INTRODUCTION

The air quality in indoor environment affects human comfort in a multitude of ways, depending on the contaminant. Airborne contaminants range from toxic substances such as carbon monoxide to nuisance matter such as large dust particles. There are literally thousands of air contaminants, each having different effects on the human body. It is necessary to discuss how the body deals with the contaminants themselves and the symptoms they inflict on the human body .The effects of airborne contaminant on humans vary greatly with the nature and type of contaminant. Gases, which enter the body through the respiratory system, are transferred into the blood stream by the alveoli and then carried throughout the body. Once inside the bloodstream, the contaminant(s) can be responsible for a variety of ailments, not just respiratory problems but physical, neurological, mental and behavioral problems (Rapp, 1985).

It is also possible that contaminants may enter the human body through skin absorption. Typically, the skin is an excellent protective barrier for the human body; however, it is capable of absorbing contaminants. Potentially, the contaminants may then enter the bloodstream, in turn affecting various organs throughout the body. This is the case with some pesticides. Other toxins, such as acids, alkalis, organic solvents, and bleaches, destroy the skin's barrier and cause harm at the site of contact.

Hospitals and other healthcare facilities are complex environments that require ventilation for comfort and to control hazardous emissions. Indoor Air Quality (IAQ) is more critical in healthcare facilities due to the hazardous microbial and chemical agents present and the increased susceptibility of the patients. To design and construct ventilation system that is capable of efficiently fulfilling all requirements, often even contradictory, is a great challenge. In addition, the importance of good indoor climate is not yet unanimously recognized. Therefore, nosocomial infections due to contaminated air continue to cause unnecessary costs and sufferings, and healthcare personnel remain subject to several occupational exposure risks.

Even though airborne-spread infectious agents are relatively few compared to total number of infectious microbes, one should be aware of them. There are several bacteria, viruses, and fungi that can be transmitted through the air. The possibility of airborne infection varies much with the type of the microbe. Medical intervention of certain diseases changes the patient to become exquisitely susceptible to common opportunistic environmental microbes.

Recognition of hazards requires understanding of the variety of hazardous agents found in health care facilities. The presence of airborne biological and chemical agents and their risk factors must be critically analyzed in order to organize an effective indoor air quality safety program where the resources are allocated optimally to reduce risks from airborne hazards. Healthcare personnel are occupationally exposed to several potentially harmful gases, vapors, and dusts. Adverse health effects may be caused by exposure to disinfectants and sterilants. Realizing that the patient is administrated medications that can cause hazardous occupational exposure to the healthcare worker, is also essential (Healthy Buildings, 2000).

The comfort air conditioning is defined as "the process of treating air to control simultaneously its

temperature, humidity, cleanliness, and distribution to meet the comfort requirements of the occupants of the conditioned space." (ASHRAE Fundamentals, 1981).
The ASHRAE standard 55-1966, targeting " Thermal Environmental Conditions for Human Occupancy" introduced a definition for thermal comfort which has become widely used and quoted "Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment."

In regulating body temperature the brain continuously compares body temperatures to desired levels and makes physiological adjustments the work of (Hardy et al., 1971) suggests that the effort of regulating body temperature affected our perception of comfort. The World Health Organization (WHO) defines health as "a state of complete physical, mental, and social well-being and not merely the absence of disease or disability". (Last, 1983); defines health as "a state characterized by anatomic integrity, ability to perform personally valued family, work, and social roles; ability to deal with physical biologic; and social stress; a feeling of well-being; and freedom from the risk of disease and Untimely death".

(Higgins, 1983); defines as adverse health effect as a biological change that reduces the level of well being or functional capacity. Maintaining human health depends on a balanced interaction between a number of complex factors. As the definition implies, simply being free from physical disease or illness does not qualify "good health". The components of mental and psychological well being are crucial to human health. Indeed the mind is powerful; individuals who perceive a physical threat to their health may incur deterioration in their quality of life, perhaps temporarily, real or perceived. Similar to the notion of health is the notion of human comfort; it too is dependent on numerous variables (Lee et al., 1996).
Achieving occupant health is the result of a collaborative effort of environmental conditions, such as:

- Indoor air temperature;
- Relative humidity;
- Airflow velocity;
- Pressure relationship;
- Air movement efficiency;
- Illumination;
- Sound and noise;
- Air quality; and
- Other factors.

PROBLEM ANALYSIS

Several earlier researches were concerned with the proper design of the airflow characteristics, such as, the air velocities, temperatures, and relative humidity. Such concern included all-environmental factors of healthcare facility but ignored the airflow movement efficiency thus restricting the attempts to obtain optimum designed healthcare facility. Well designed and maintained air characteristics serving healthcare facilities with properly balanced air distribution are probably the single most important factor in the IAQ equation (Bhattacharyya, 2000).

The efficiency of the ventilation systems depends mainly on the efficacy of the airside design. The efficacy of the airside design depends, in turn, on the locations of the supply outlets and extraction ports. Most of mechanical engineers face the common problem "where can we locate the supply outlets and extraction ports" and "what is the proper direction of the airflow inside the medical space". There are also some considerations of the energy consumption optimization lead the mechanical engineer to follow the unsuitable designs.

There are several divisions in each hospital; each of them requires different type of ventilation. This situation can create a problem in the small facilities, which have limited number of floors or small area. The most common critical departments in any healthcare facilities are surgery, isolation, nursery, and critical care divisions. To overcome the problem of ineffective ventilation, the guideline of proper location selection of the supply outlets and extraction intakes should be established.

VENTILATION REQUIREMENTS

The effective ventilation should be defined firstly to establish the proper design consideration. The effective ventilation is the process, which is well designed to provide the fresh and clean air continuously, and to extract the pollutant air and contamination. The improper pressure relationship can destroy the good design of the HVAC airside system. So, the proper ventilation starts by providing a proper pressure relationship between the different spaces in the hospital, and followed by providing a proper design of the airside parameters

Pressure relationship

Ventilation recommendations for comfort, asepsis, and odor control in areas of acute care hospitals that directly affect patient care are presented by the healthcare standards. Ventilation in accordance with ASHRAE standards 62, Ventilation for Acceptable Indoor Air Quality (AIAQ) should be used for areas where specific standards are not given. Specialized patient care areas, including organ transplant and burn units, should have additional ventilation provisions for air quality control as may be appropriate (ASHRAE, 2002). Design of ventilation system must, as much as possible, provide air movement from clean to less clean areas. In critical care areas, constant volume systems should be employed to assure proper pressure relationships and ventilation, except in unoccupied rooms, Figure 1.

Air movement efficiency

Systems serving highly contaminated areas, such as autopsy and infectious isolation rooms, should maintain a negative air pressure within these rooms relative to adjoining rooms or the corridors (Murray et al., 1988). The negative pressure difference is obtained by supplying less air to the area than is exhausted from it (CDC, 1994). This pressure differential causes air to flow into the room through various leakage areas (e.g., the perimeter of doors and windows, utility/fixture penetrations, cracks, etc.) and prevents outward airflow.

Protective isolation rooms exemplify positive pressure conditions or opposite conditions. Exceptions to normally established negative and positive pressure conditions include surgical operating theatres where highly infectious patients my be treated (e.g., surgical operating theatres in which bronchoscopy or lung surgery is performed) and infectious isolation rooms that house immunosuppressed patients with airborne infectious diseases such as tuberculosis (TB). These areas should include an anti-room between the operating or isolation room and the corridor or other contiguous space. The anti-room should either be positive to both the room and contiguous space or negative to both the room and the contiguous space, depending on local fire and smoke management regulations. Either technique minimizes cross contamination between patient area and surrounding areas.

Differential air pressure can be maintained only in an entirely sealed room. Therefore, it is important to obtain a reasonably close fit of all doors and seal all walls and floor penetrations between pressurized areas. This is best accomplished by using weather stripping and drop bottoms on doors. The opening of a door between two areas instantaneously reduces any existing pressure differential between them to such a degree that its effectiveness is nullified. When such openings occur, a natural interchange of air takes place between the two rooms due to turbulence created by the door opening and closing combined with personal ingress/egress. For critical areas requiring both maintenance of pressure differentials to adjacent spaces and personnel movement between the critical area and adjacent spaces, the use of appropriate air locks or anterooms is indicated. In general, outlets supplying air to sensitive ultra clean areas should be located on the ceiling, and perimeter or several extract outlets should be near the floor. This arrangement provides a downward movement of clean air through the breathing and working zones to the floor area for extract. Infectious isolation rooms should have supply air above and near the doorway and extract air from near the floor, behind the patient's bed. This arrangement is such that clean a ir first flows to parts of room where workers or visitors are likely to be, and then flows across the infectious source and into the extract. Thus, non-infected persons are not positioned between the infectious source and the extract location (CDC, 1994). The bottom of the return or extract openings should be at least 75 mm above the floor.

ARCHITECTURAL REQUIREMENTS

To build effective ventilation system to achieve the optimum hygiene conditions need more careful and collaborative work. IAQ is not responsi ble from the mechanical and environmental engineers only. Making IAQ a top priority in the healthcare facilities starts with the building design (Streifel, 2000). The healthcare application appears as a most important application among the invironment applications. In the last decades, many researches were concerned with optimum solution to improve the productivity of hospital systems through improvements in the design of hospital facilities and in the utilization of hospital space (Smalley et al., 1966).

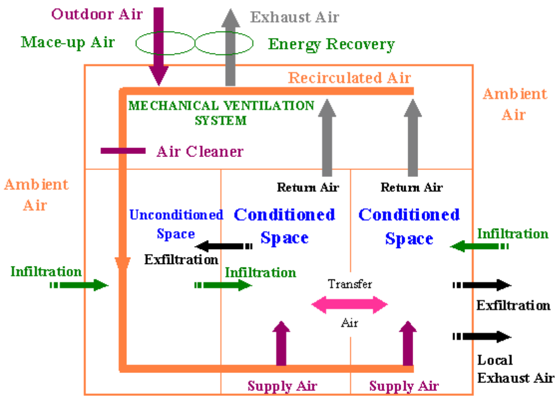

Figure 1 Air Exchange within the space and controlled ventilation

An important principle of facilities had been arisen, in that time, which is "The primary and overriding purpose of any physical facility is to promote the attainment of objectives of the enterprise in which the facility is to be used". It should be noted that the principle introduced here does not state any comments regarding the quality of physical facility performance during the facility service. It can be concluded that, as an engineer, he should translate the functional needs of department into terms understandable to the architect and, as a hospital-oriented person, he could treat architectural requirements as constraint in the design of hospital systems, which serve the operational needs of the various departments.

AIR DISTRIBUTIONS

The airflow patterns in operating theatres are very important factor in obtaining good indoor air quality. Figures 2, 3, 4 and 5 show the room configuration, predicted air velocity pattern, air temperature and relative humidity in a typical operating theatre. The present work made use of the computer Package, which developed, by (Khalil, 1999) . The program solves the differential equations governing the transport of mass, three momentum components and energy in three-dimensional configurations. The equations are typically expressed as:

$$div\left(\rho V\Phi - \Gamma_{\Phi,eff}\,.\,grad\,\Phi\right) = S_{\Phi}$$

A typical operating theatre configuration is shown in figure 2 for a room that represents actual surgical operating theatre and including the operating table. The room dimensions are 6.0 m length (L), 5.0 m width (w), and 3.0 m height (H). The operating table has a length of 2.0 m and a width of 1.0 m, and is located at 1.0 m high as shown in figure 2.

Ceiling Square Perforated Supply air grilles were located at the center of the room with total dimensions 1.8 m x 1.8 m (9 modules of 0.6 m x 0.6 m with absolute filter banks). The partial walls dropped 200 mm from ceiling. The extract ports were located on the left and right walls, see figure 2. The return port dimensions are 0.6 m x 1.8 m. the lower outlet center point is located at 0.7 m from the floor. The higher return port center point located at 1.7 m from the floor (Kameel, 2002).

According to HTM 2025, the down flow of supply air should cover a minimum projected area of 2.8 m by 2.8 m. The boundary of the supply air diffuser should be provided with either partial or full wall rim. A fixed partial wall that terminates at 2 m above the finished floor level (FFL) was introduced. The discharge velocity at the diffuser is a crucial factor to ensure that sufficient air reaches the operating table level. HTM quotes this as 0.38 m/s as a minimum.

From previous results, one can assess the merits of such air supply outlets and the extract ports design and arrangement in the surgical operating theatre. Previous researches on HVAC systems in the surgical operating theatres recommended the downward flow as optimum for the air distribution in that sensitive place. Some other studies for air distribution indicated that the direction of airflow is critical.

The designers of the HVAC systems should consider the importance of the air distribution; the positioning of air supply outlets, air extract ports, and partial walls may be useful to maintain the air environment in the surgical operating theatre.

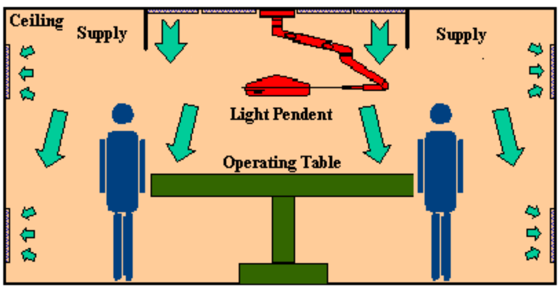

Figure 2 Schematic sketch of the surgical operating theatre (elevation view)

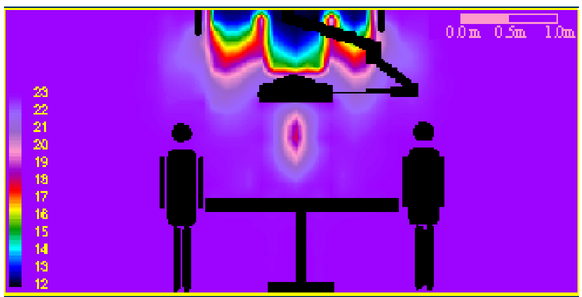

Figure 4 Predicted Temperature Contours

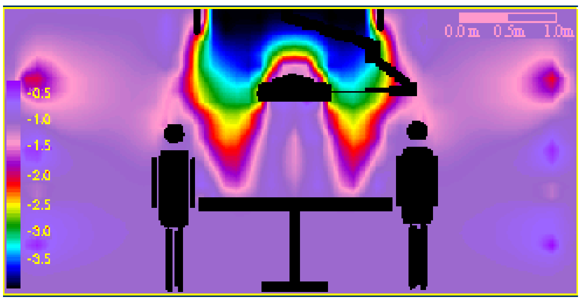

Figure 3 Predicted Velocity Contours

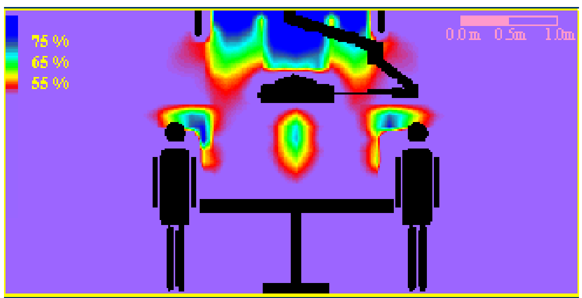

Figure 5 Predicted Relative Humidity Contours

The higher extract ports were recommended to decrease the airflow direction towards the patient. This appeared strongly in the prediction of the airflow pattern over the operating table. The higher extract prevented the high level of turbulence in the airflow direction near the operating table. The partial walls were so effective in directing of the airflow to obtain the most benefit of the cooled air. The presence of the partial wall had a positive influence on the airflow distribution, it also indicated a great effect on eddies formation in the operating area over the operating table surface. The height of the partial walls is an important factor in the effectiveness of the partial walls on the airflow.

The presence of the operating table in the operatin g area influenced the air distribution. The simulation of the vacant room may be useful only in the predicting velocities but that simulation doesn't predict accurate distribution of airflow turbulence over the operating table. Meaningful predictions of th e flow characteristics over the operating table surface enrich our understanding of the flow action near the operating area. The turbulence level over the operating area was affected by the presence of operating table itself, the position of the air supply outlet, the distribution of the extract ports, and the discharge and extract velocities. The orientation of the operating table has a pronounced effect on the air characteristics in the operating area. The higher extract ports enhance the air actions near the edges of the operating table, which decreases partially the penetration of the airflow of the supply outlet.

The turbulence distribution over the operating table surface exhibited similar trends, and indicated higher values on the edge of the table an d the lower values in the middle. Such distribution was anticipated due to the presence of the bluff bodies (operating table) downstream the jet flows. The effect of partial walls on the turbulence distribution was limited. From the numerical predictions shown here it was found that the presence of temperature difference (room/supply) has no great influence on the airflow pattern .

RECOMMENDATIONS

One can introduce the factors that affect the IAQ in healthcare application in two main groups, namely ; architectural design group and airside system design group. The following points will show the two main design groups and the internal sub-factors.

- Architectural Design Group
  - ∗ Geometrical Configurations
    - Space dimensions.
    - Distribution of openings in the walls (doors, and windows).
    - Relative position of the division in the facility to the other spaces.
  - ∗ Internal furniture and equipment
    - Wall mounted devices and accessories.
    - Thermal sources' locations and its equipment distribution.
    - Pollutant sources' locations.

- Airside System Design Group
  - ∗ Supply Design
    - Supply air-conditions (velocity, direction, temperature, and relative humidity).
    - Supply air diffuser(s) locations.
    - Supply air diffuser(s)size and distribution.
  - ∗ Extraction Design
    - Extract grilles' locations.
    - Extract grilles' distribution.
  - ∗ Airflow distribution and HVAC design

ARCHITECTURAL AND MECHANICAL DESIGN RECOMMENDATIONS

The design experiences of several hospital and corresponding researches to select the optimum HVAC airside design deduced the following recommendation s:

- The airflow distribution is influenced by the distribution of medical furniture and equipment. Indeed, the existing of equipment closing to the extraction ports affects the airflow pattern and participates to create recirculation zones. So the architectural should provide the optimum space during the design, which enhance the arrangement of the medical furniture and equipment.
- In horizontal ventilation, the supply outlets and extraction ports should be located in the wide opposite walls to save the energ y and obtain the optimum airflow pattern. So, the architectural should provide one of the opposite walls couples without any architectural obstacles.
- In vertically downward ventilation, the supply outlets should be located in the ceiling as a one supplying area, not separate perforated diffusers, (Kameel et al., 2003). So, the architectural should provide a total height for the floor of 3.6 m at least, also, should provide one of the opposite walls couples without any architectural obstacles to locate the extraction ports for optimum air distribution.
- It is found that in the vertically downward ventilation the using of upper level of extraction could optimize the airflow distribution. In some architectural designs, this option is impossible to be applied because of the difficulties of duct network distribution. Some of mechanical designers exclude this option to reduce the owning price of the system.
- The airflow should be directed from the clean space to the less clean space. In some hospital, the

same floor is divided to different departments. Actually, the airflow among different spaces could not be restricted, due to the difference of HVAC systems that serve each division. The critical space should be served by constant air volume system, and the uncritical space could be served by a variable air volume system. In several situations the uncritical spaces that are close to the critical space (negative pressure) become unoccupied, so it receive the air from the critical space by errors. So it should be located all the critical spaces in same area.

It is recommended that architectural and HVAC designers should follow the following recommendations to achieve the optimum healthcare facility design without any future risks, Figure 6.

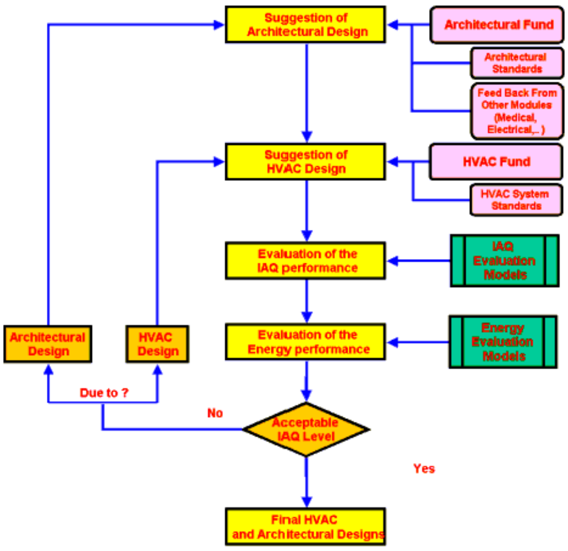

Figure 6. Flow-Charts of Architectural and HVAC Design

ACKNOWLEDGMENT

Thanks and gratitude are respectfully due to Cairo University New Kasr El-Aini Teaching Hospital for the technical support throughout the work.

NOMENCLATURE

ρ	Air density, kg/m^3
Φ	Dependent variable (velocity components, k, H…. etc).
V	Velocity vector
$\Gamma_{\Phi,eff}$	Effective diffusion coefficient.
S_Φ	Source term of Φ.

REFERENCES

ASHRAE Fundamentals, 1981, ASHRAE, Atlanta.
ASHRAE Fundamentals, 2002, ASHRAE, Atlanta.
ASHRAE standards, 55-1966, ASHRAE, Atlanta.
Bhattacharyya, S. 2000. Indoor air quality (IAQ): concerns & considerations in health care facilities, Albert Kahn Inc., AKA News – Articles, Published in Engineered Systems magazine, Electronic Publishing.
CDC. 1994. Guidelines for preventing the transmission of mycobacterium tuberculosis in health-care facilities, 1994, U.S. Dept. of Health and Human Services, Public Health Service, Centers of Disease Control and Prevention, Atlanta.
Hardy, J.D., Stolwijk, J.A.J., and Gagge, A.P. 1971. Comparative physiology of thermoregulation, Chapter 5. Springfield, III: Charles C. Thomas.
Healthy Buildings. 2000. Indoor Air Quality in Hospitals and Other Health Care Facilities, Workshops, Workshop 22, IAQ in Hospitals, Initiated by ISIAQ Task Force IV.
Higgins, I.T.T., 1983. What is an adverse health effect?, APCA Journal, 33:661-63.
Kameel, R. 2002. Computer aided design of flow regimes in air-conditioned operating theatres, Ph.D. Thesis work, Cairo University.
Kameel, R., and Khalil, E.E. 2003. Simulation of flow, heat transfer & relative humidity characteristics in air-conditioned surgical operating theatres, 41st Aerospace Sciences Meeting and Exhibit, AIAA 2003-85, Reno, Nevada.
Khalil, E. E., 1999, Fluid Flow Regimes Interactions in Air Conditioned Spaces, Proc. 3 rd Jordanian Mech. Engineering Conference, pp. 79, Amman, May 1999.
Last, J.M. 1983. Public health and human ecology, Appleton & Lange, New York.
Lee, T.G., De Biasio, D., and Santini, A. 1996. Health and the built environment: Indoor air quality, Vital Signs Curriculum Materials Project, Health and the Built Environment, The University of Calgary, 1996.
Murray, W.A., Streifel, A.J., O'Dea, T.J., and Rhame, F.S. 1988. Ventilation protection of immune compromised patients, ASHRAE Transaction 94(1):1185-1192.
Rapp, D. 1985. Allergies and the hyperactive child, New York: Simon and Schuster, Inc., 1985.
Smalley, H.E., and Freeman, J.R. 1966. Hospital Industrial Engineering – A guide to the improvement hospital management systems, Reinhold Publishing Corporation, New York, 1966
Streifel, A.J. 2000. Health-Care IAQ: guidance for infection control, HPAC Journal, 28-36, October 2000.
WHO. 1987. Air Quality Guidelines for Europe, European Series No. 23, WHO, Copenhagen.