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Three-dimensional Thermal Comfort Analysis for Hospital Operating Room with the Effect of Door Gradually Opened

Part (I) Effect on Velocity and Temperature Distributions

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Abstract

This study presents a three-dimensional analysis for thermal comfort 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 the ceiling and exhausted through low sidewall grilles sustaining 20 ACH inside the room. Steady-state heat and mass transfer in the room are simulated by employing computational fluid dynamics modelling approach. Solutions of the distribution of airflow velocity and temperature are presented and discussed in this part of study, part (A). The second part, part (B), deals with the mean age of the air and predicted mean vote as a judge of thermal comfort (it is a scale proposed by ASHRAE standards to account for thermal sensation , the index scale indicates +3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool and -3 cold) . The simulation results show a good agreement with previous published data. Effects of door opening on thermal comfort are explored. The study numerically assured the necessity of pressurization and the bad influence of door opening.

Keywords: CFD; Heat and mass transfer; Air conditioning; Thermal comfort; Pressurization; HVAC.

1. Introduction

Operating room flow patterns have constituted a great importance in field of HVAC research. The air distribution in such rooms should ensure proper ventilation with no dead ones (regions of zero velocity) and proper thermal comfort conditions. The pressurization of surgery theaters is of critical importance to guarantee the required cleanliness in such clean areas. As a result, operating room flows have been simulated experimentally and numerically. Balaras et al [1] identified the most common problems in all or the majority of the operating rooms during the audit campaign of 20 operating rooms in 10 different hospitals, related to the HVAC system operation and performance, indoor conditions and physical parameters, were insufficient number of air changes, mostly due to obsolete AHUs, improper system sizing or poor maintenance and unsatisfactory indoor air temperature and spatial variations, mostly due to malfunctions of AHUs.

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Constantinos A. Balaras et al [2] reviewed published standards and guidelines on design, installation, commissioning, operation, and maintenance of HVAC installations in hospital operating rooms. Chow and Yang [3,4] used CFD analysis to simulate the temperature distribution and airflow pattern 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. Fox et al [5] showed that preventive maintenance assures safe and uninterrupted operation. Regular monitoring and air sampling can contribute to early detection of possible defects and problems. Gerald Cook et al [6] studied the Hepa-filtered air distribution inside operating rooms, where air changes can range from 70 – 160 ACH,and methods to control room pressurization. Humphreys et al. [7] showed through an experimental survey that the most common problems in operating rooms were operable windows in the older buildings, which are still used for natural ventilation, they should be sealed and poorly maintained ducts and diffusers. Kameel and Khalil [8] proposed guidance to architectural and mechanical engineering designers to optimize the comfort and hygiene conditions in operating theatres. K.-G. Nilsson et al [9] investigated the addition of an instrument table supplied with fixed ultraclean laminar air flow and placed alongside the existing main laminar air flow unit, to determine its physical and bacteriological effect on the main unit. Memarzadeh and Manning [10] simulated air flow in an operating room using CFD and showed that a laminar flow condition is the best choice for a ventilation system. Monika Woloszyn et al [11] studied the air flow patterns in an operating room with a diagonal air-distribution system subjected to both experimental measurements and numerical modeling. Noie-Baghban et al [12] studied heat recovery in ventilation systems, from the exhausted air to the fresh air supply, which is usually accomplished using a plate heat exchanger in the AHU. Posner et al. [13] compared their measured and simulated results for indoor airflow in a single test room equipped with an internal partition. Son et al [14] presented a three-dimensional analysis for thermal comfort and contaminant removal in a hospital operating room. The room model included a patient lying on an operating table, four surgical staff members standing around, and surgical lights above the patient with side-wall grilles. Wecxsteen et al [15] illustrated how the efficiency of an air-distribution system in preventing nosocomial infections depends on factors such as the position of the air inlet and outlet, the air-inlet velocity or air-change rate, the presence of airflow-perturbing elements (equipment, staff) and the type of operation being performed.

From the previous review the effect of door opening is not widely investigated so the main objective of the present work is to study the air distribution in an operating room with door opened successively and its effect on velocity and temperature and to assure the necessity of pressurization. The work in this part of paper is mainly devoted to introduce the study in part B of the paper that deals with mean age of air and its predicted mean vote to judge thermal comfort.

2. Numerical details

2.1. Governing equations

To assess thermal comfort and contaminant removal, air velocity, temperature, and water vapor and contaminant concentrations need to be determined. These can be found by solving the system of coupled governing equations for the conservation of mass (for the whole air mixture as well as for each species), momentum, and energy. Steady-state incompressible laminar flow of air as a multi-component fluid, which includes dry air, water vapor, and a contaminant gas, is considered. The fluid properties are taken as constants except the varying density for buoyancy term in the momentum equation. The equation for the conservation of mass applied to the air mixture as the carrying fluid is given by

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

The buoyancy force term arising from density variation is included by means of the Boussinesq approximation based on the assumptions that the variation of fluid density affects only the buoyancy term and the fluid density is a function of temperature only. The equation for the conservation of linear momentum is given by

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right] \quad (2)$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right]+\rho g\beta\left(T-T_{ref}\right) \quad (3)$$

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left[\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right] \quad (4)$$

Assuming that there is no heat generation, thermal conductivity is scalar, energy fluxes due to inter-diffusion and Dufour effect are negligible, and the equation for the conservation of energy is given by

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right] \quad (5)$$

Assuming that the mass diffusivities of species in the airflow are scalars, thermal diffusion is negligible, and there is neither source nor chemical reaction, the equations for the mass conservation of water vapor is given by

$$u\frac{\partial w_w}{\partial x}+v\frac{\partial w_w}{\partial y}+w\frac{\partial w_w}{\partial z}=D_w\left[\frac{\partial^2 w_w}{\partial x^2}+\frac{\partial^2 w_w}{\partial y^2}+\frac{\partial^2 w_w}{\partial z^2}\right] \quad (6)$$

In tensor form,

$$u\,.\nabla w_w = D_w\nabla^2 w_w \quad (7)$$

Similarly contaminant transport is given by

$$u\frac{\partial w_c}{\partial x}+v\frac{\partial w_c}{\partial y}+w\frac{\partial w_c}{\partial z}=D_c\left[\frac{\partial^2 w_c}{\partial x^2}+\frac{\partial^2 w_c}{\partial y^2}+\frac{\partial^2 w_c}{\partial z^2}\right] \quad (8)$$

In tensor form,

$$u\,.\nabla w_c = D_c\nabla^2 w_c \quad (9)$$

An operating room of dimensions (6.1 m x 4.3 m x 3.0 m) is considered which has the basic arrangement as shown in figure (1). All the exhaust grilles have the same size of (0.61 m x 0.36 m). This room can be modelled at full scale with proper consideration. An x–y–z co-ordinate system is attached to the model with the origin located at the bottom left corner of the room. The lying patient is modelled as a horizontal rectangular box (1.7 m x 0.3 m x 0.5 m) in the middle of the room. Its bottom surface facing the floor models the operating table, which is heat and mass insulated. The other five surfaces model the patient's body, which is maintained at constant temperature and releasing water vapor and contaminant as constant fluxes. The standing surgical staff members are modeled by vertical rectangular boxes (1.7 m x 0.3 m x 0.5 m). These staff member models are considered as surfaces of constant temperature and constant water vapor flux but no contaminant flux. The surgical light is also modeled as a rectangular box (0.7 m x 0.65 m x 0.3 m) above the patient, whose bottom surface (facing the patient) is defined as ''lamp face'' entity, on which the major heat flux goes through; and other surfaces are defined as ''lamp back'' entity, on which a smaller heat flux goes through & a door (2m x1m) is located in the mid of a wall as shown in figure (1).The boundary conditions on the exhaust opening is unknown and to be solved for as a part of the solution of the flow over the whole domain. The other boundary conditions left unmentioned are assumed to be zero velocity and totally insulated to heat and mass (e.g. zero velocity and neither heat flux nor mass flux at solid surfaces such as walls, floor, and ceiling; no contaminant flux from the staffs' body, etc.). Numerical values of the boundary conditions used for the solution are listed in table (1).

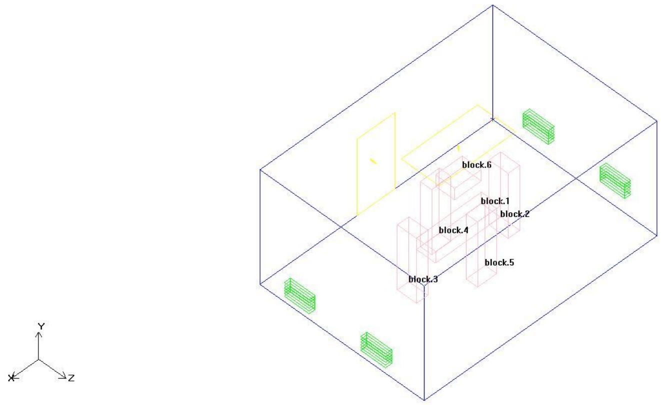

Figure (1) modelled room

TABLE (1) BOUNDARY CONDITIONS FOR THE PROBLEM

boundary	Velocity	Temperature	Water vapor	contaminant
Light face	$u_x = u_y = u_z = 0$	$q = 100$	$q_w = 0$	$q_c = 0$
Light back	$u_x = u_y = u_z = 0$	$q = 5$	$q_w = 0$	$q_c = 0$
patient	$u_x = u_y = u_z = 0$	$T = 34$	$q_w = 2.5 * 10^{-6}$	$q_c = 10^{-5}$
staff	$u_x = u_y = u_z = 0$	$T = 34$	$q_w = 4 * 10^{-6}$	$q_c = 0$
supply	$u_x = u_z = 0 \;\; u_y = -0.234\, m/s$	$T = 20$	$w_w = 0.01$	$w_c = 0$
exhaust	u_x, u_y, u_z	T	ω_w	ω_c
others	$u_x = u_y = u_z = 0$	$q = 0$	$q_w = 0$	$q_c = 0$

2.2. *Solver details*

The coupled system of equation is solved together with its boundary conditions using finite volume technique and a second order upwind scheme with suitable under-relaxation factors (0.8 for momentum, 0.75 for energy and 0.7 for contamination) for all operating parameters utilizing Ansys airpak (2.0.6). The iterative procedure for the solution is considered converged when the norm of the relative errors of the solution between iterative steps is less than a tolerance of 0.001. A grid independence study was performed and a mesh of (60*60*60) seemed satisfactory with narrower mesh beside patient, staff, supply to adopt with the steep gradients.

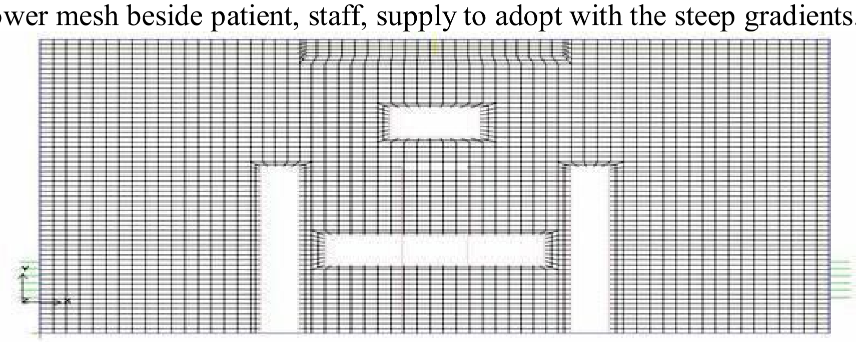

Figure (2) mesh cells on plane (z=2.15m) in the modelled room

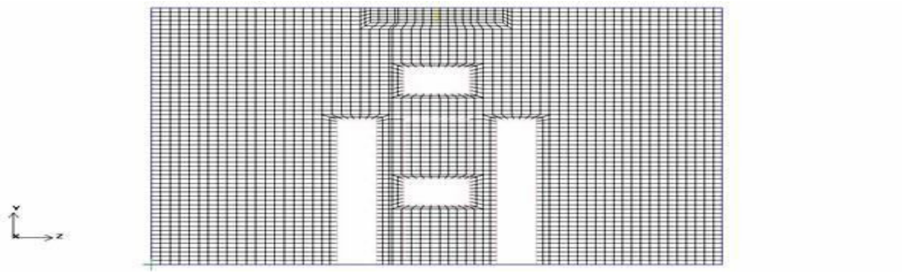

Figure (3) mesh cells on plane (x=3.05m) in the modelled room

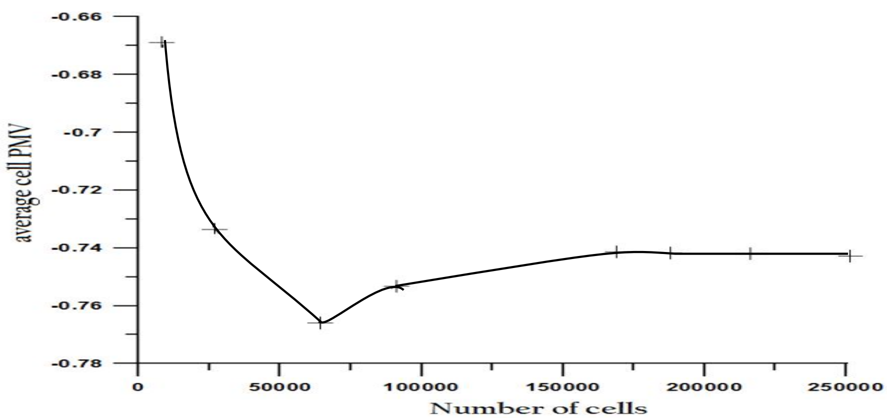

Figure (4) grid independence study

4-Validating the problem code

The code was validated by comparing with Son el al [14] with their same model. The comparison showed good agreement with past results as shown in table (2) with maximum deviation 5.56%

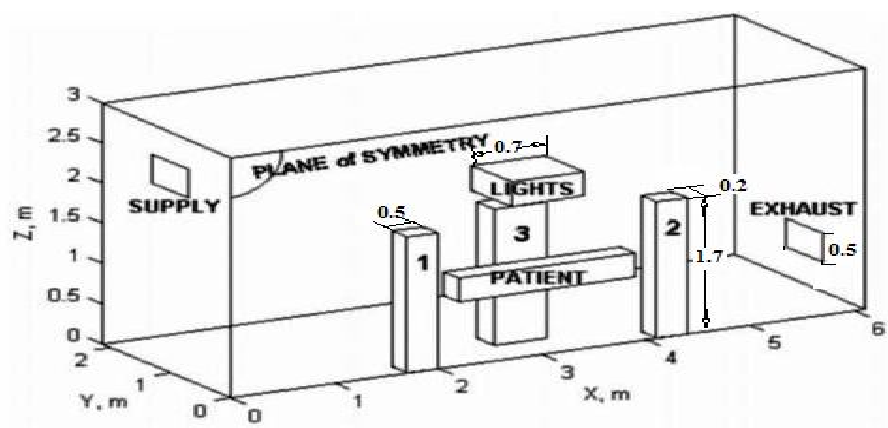

Figure (5) previous work to be compared with

TABLE (2) COMPARISON OF PRESENT CODE WITH SON ET AL [14]

	present work	previous work	Percentage deviation
Speed on a plane 5 cm beyond patient body	0.21 m/s	0.22 m/s	4.5 %
Speed on a plane 5 cm beyond staff (1) body	0.185 m/s	0.2 m/s	7.5 %
Speed on a plane 5 cm beyond staff (2) body	0.223 m/s	0.24 m/s	4.16 %
Speed on a plane 5 cm beyond staff (3) body	0.26 m/s	0.27 m/s	3.7 %
Temperature on a plane 5 cm beyond patient body	23.8 ^oC	24.1 ^oC	1.25 %
Temperature on a plane 5 cm beyond staff (1) body	22.1 ^oC	21.7 ^oC	1.8 %
Temperature on a plane 5 cm beyond staff (2) body	22.8 ^oC	21.6 ^oC	5.56 %
Temperature on a plane 5 cm beyond staff (3) body	24.2 ^oC	23.6 ^oC	2.54%

3. Results and discussion

The set of coupled equations presented in the mathematical model are solved numerically. Results are displayed for velocity and temperature distributions. To clearly visualize the results they are displayed on mid planes in x and z directions and planes that are 5 cm beyond patients and staff members.

3.1. Effect of door opening on speed contours

Speed of air within the room is within acceptable limits (<0.5 m/s). The air speed slightly decreases by the door opening. Slight recirculation appeared beyond staff members facing the door opening that become severe when door is opened more than 75^o. Slight recirculation is observed around the rest of the staff as shown in figures (6) & (7). It is noted that dead zones are observed and increased within the working zone when the door is opened. Runs are made for various over-pressurizations and exhaust grilles elevation. +25 Pa and 20 cm exhaust grilles elevation seemed reasonable and in same ranges reported by Son el al [25].

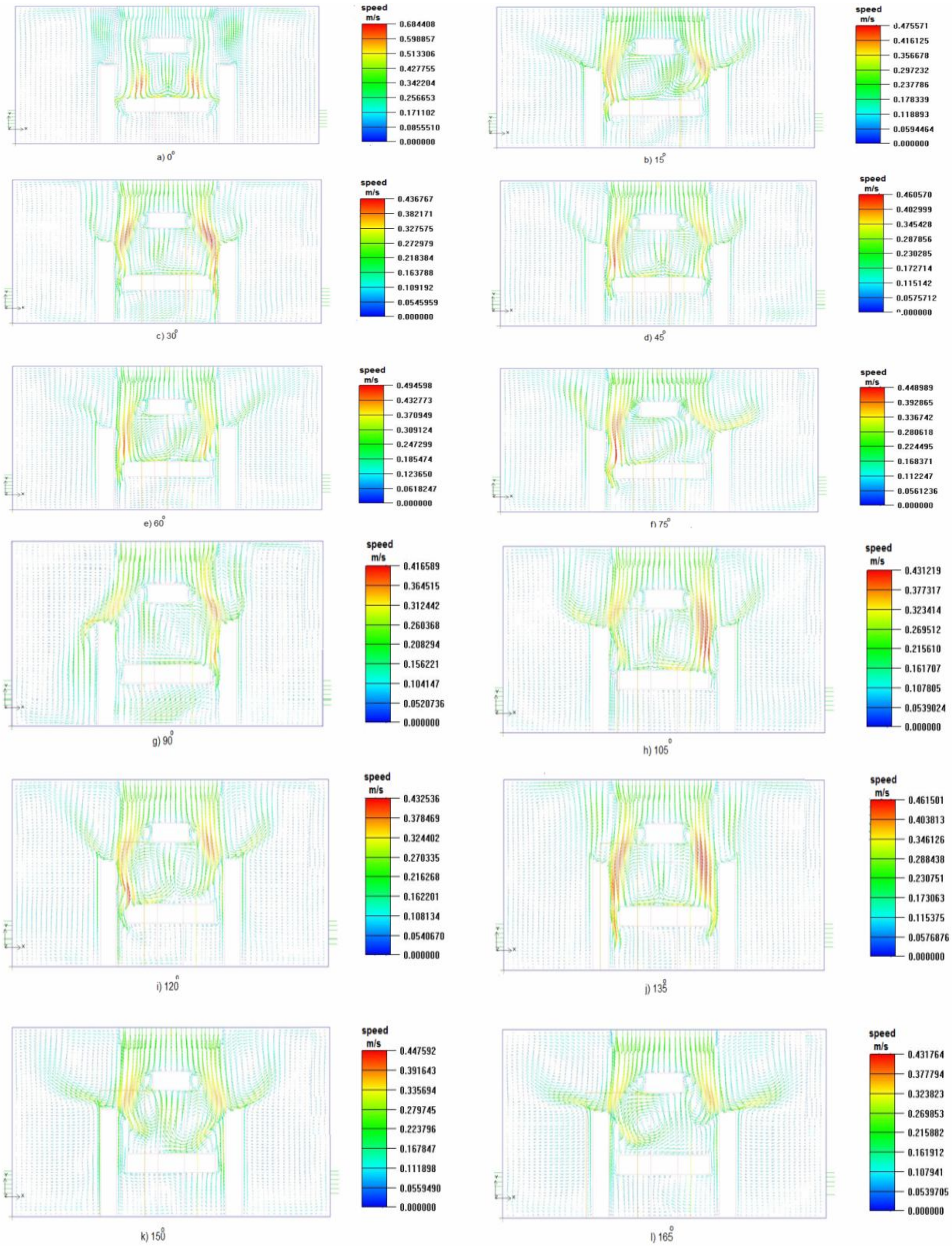

Figure (6) speed vectors on z=2.15m plane

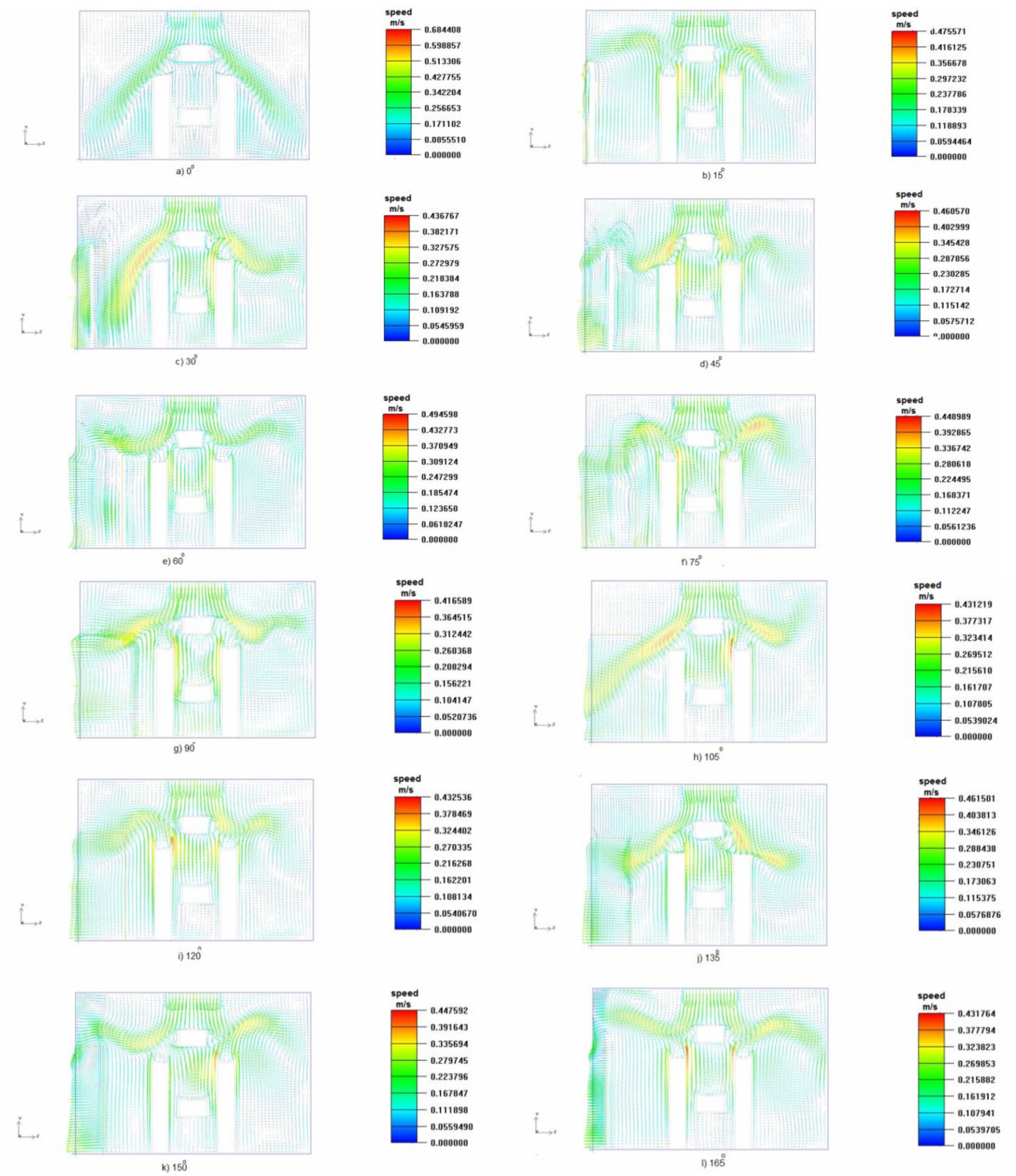

Figure (7) speed vectors on x=3.05m plane

3.2. Effect of door opening on temperature contours

Temperature inside the room gradually increases by gradual opening of the door. Patient is severely affected with hot zones (>26°C) approaching his head specially on opening more than 90^0. Staff members are affected by hot zones approaching their head specially on opening more than 60^0 as shown in figures (8), (9), (10), (11) & (12) causing deviation from comfort conditions. Throughout the room the temperature on mid-planes in both x and z directions show clearly that the hot zones approaches the upper portion of the room when the door is gradually opened this can be explained by the increased recirculation near the door which increases by its gradual opening. This is depicted in figures (13) &(14).

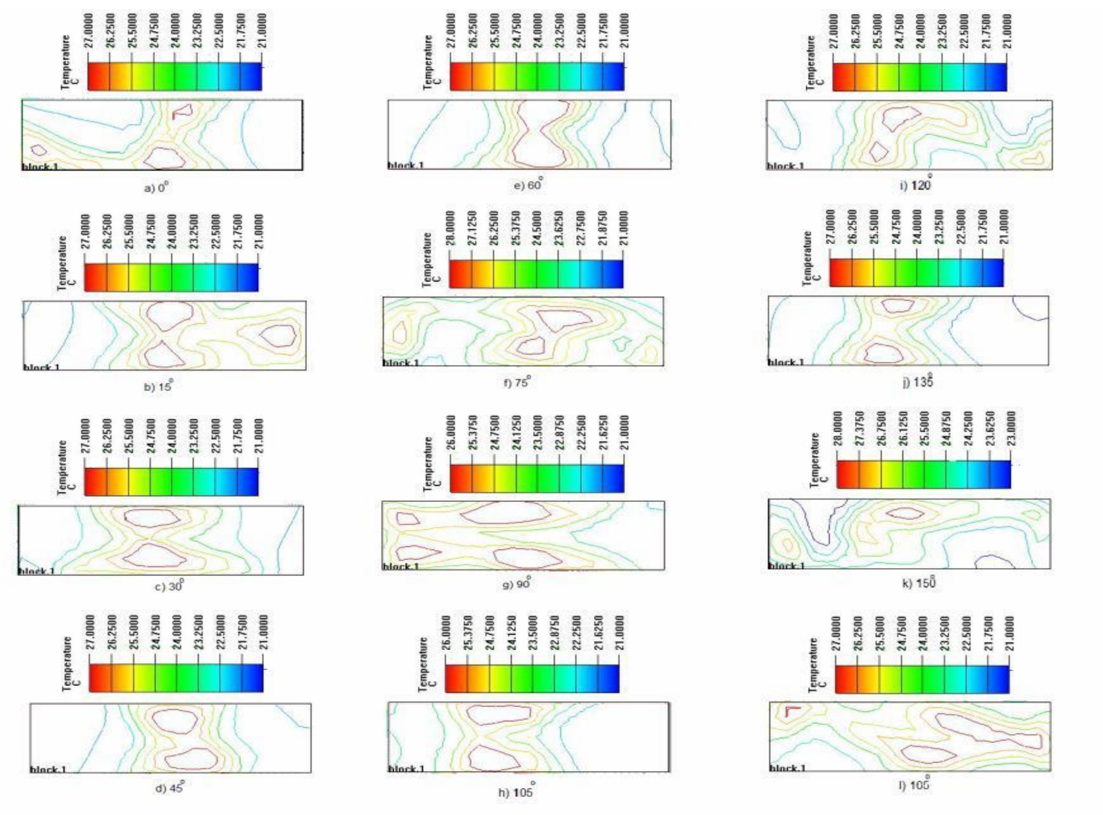

Figure (8) Isothermals 5 cm beyond patient body

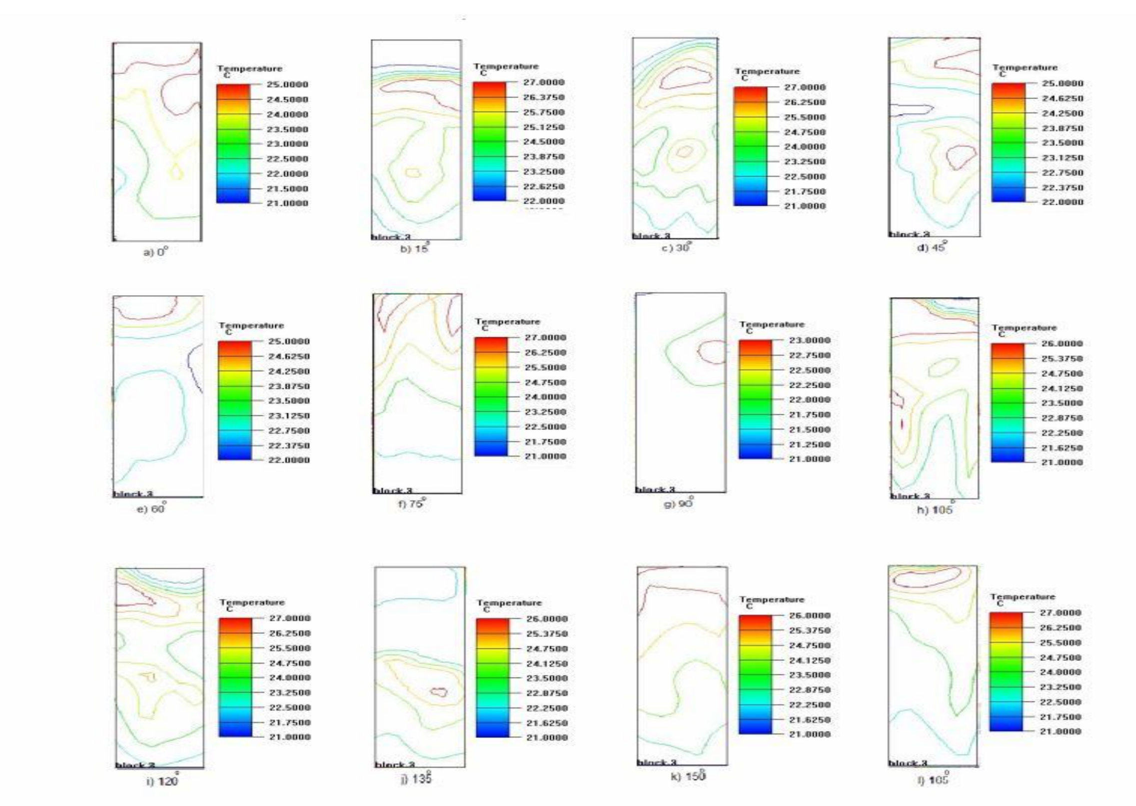

Figure (9) Isothermals 5 cm beyond staff (1) body

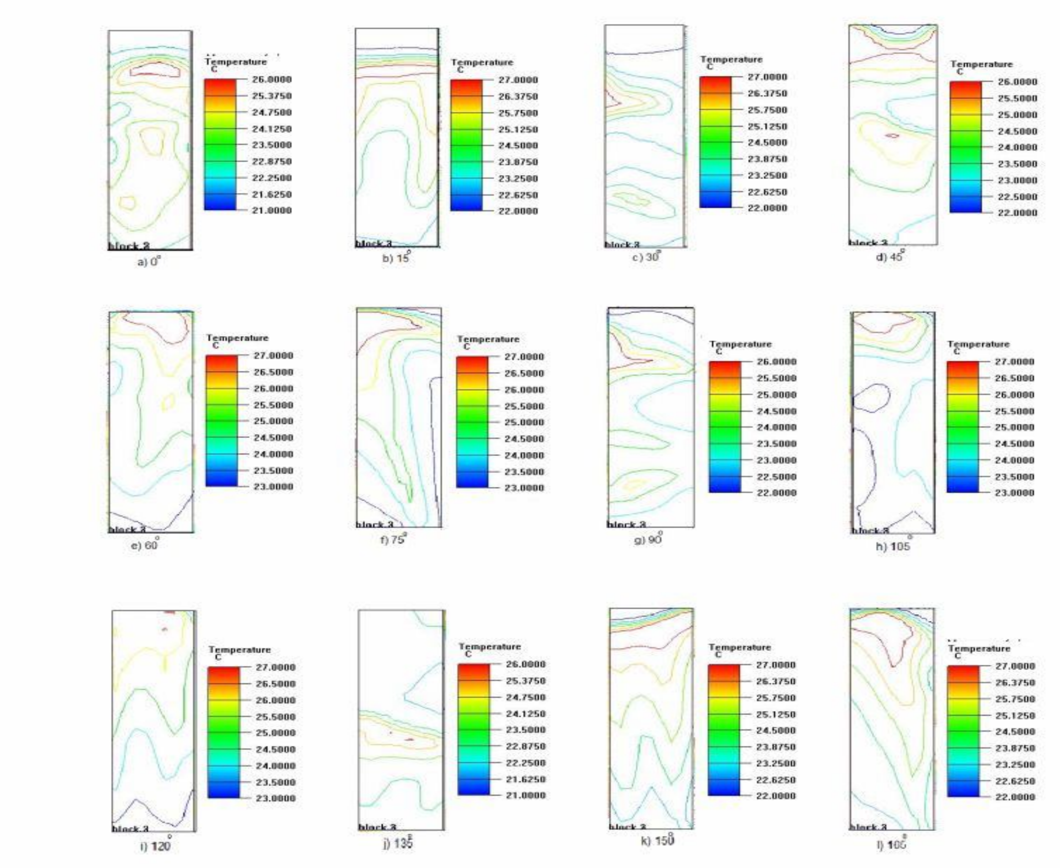

Figure (10) Isothermals 5 cm beyond staff (2) body

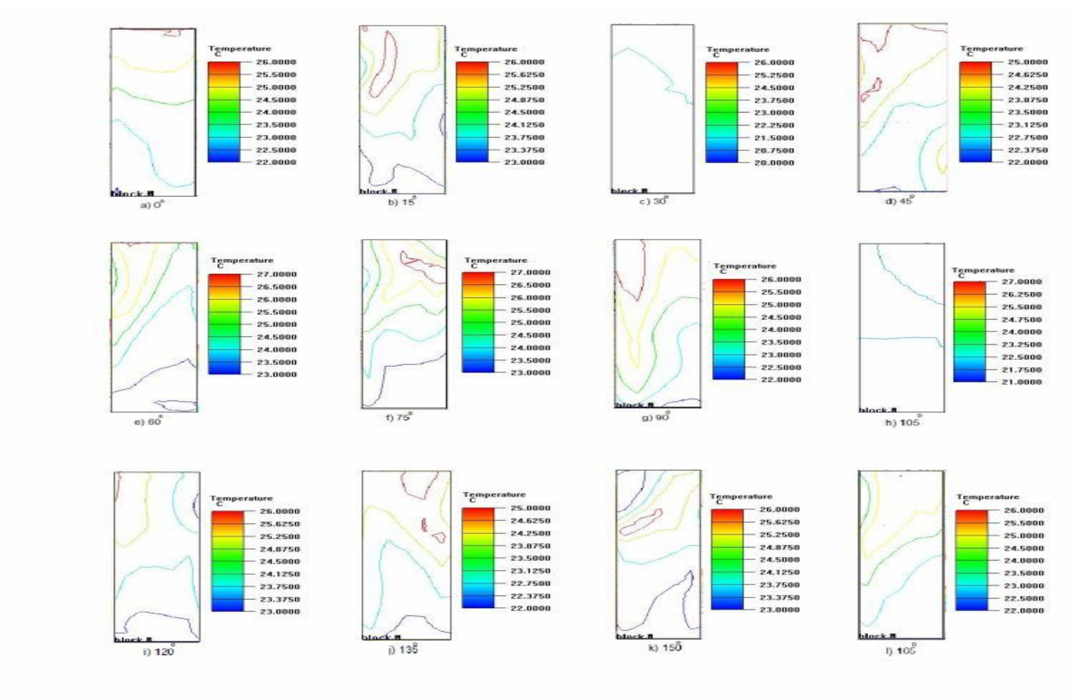

Figure (11) Isothermals 5 cm beyond staff (3) body

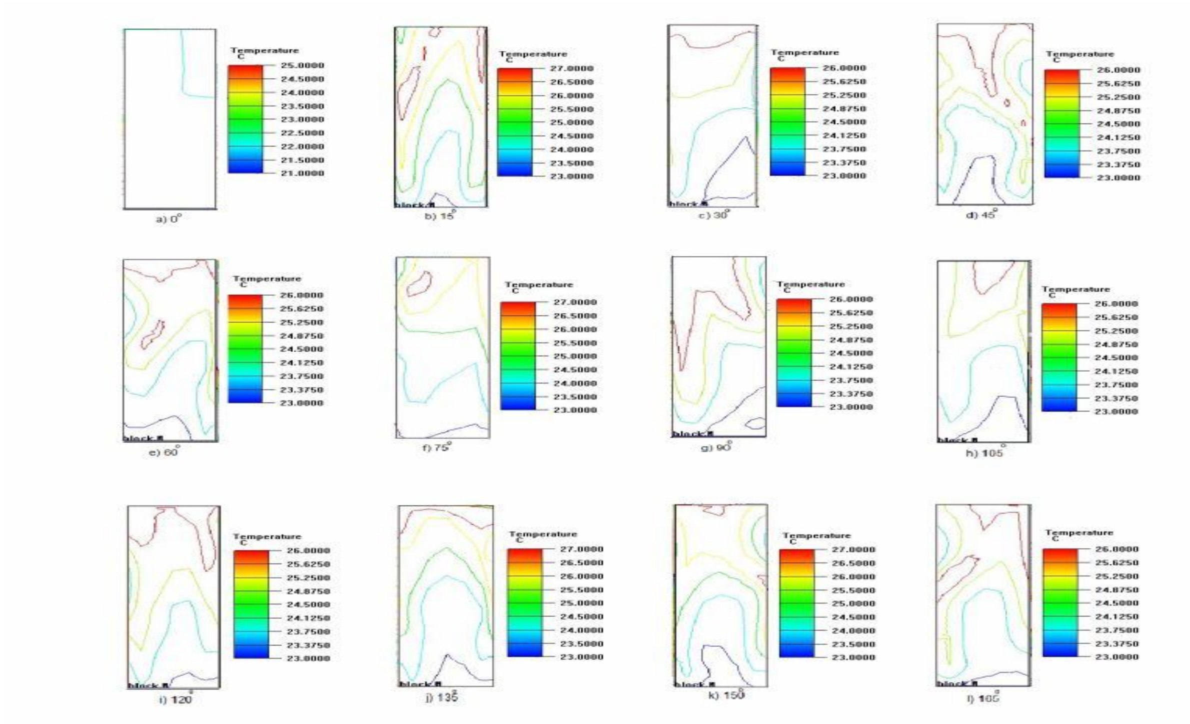

Figure (12) Isothermals 5 cm beyond staff (4) body

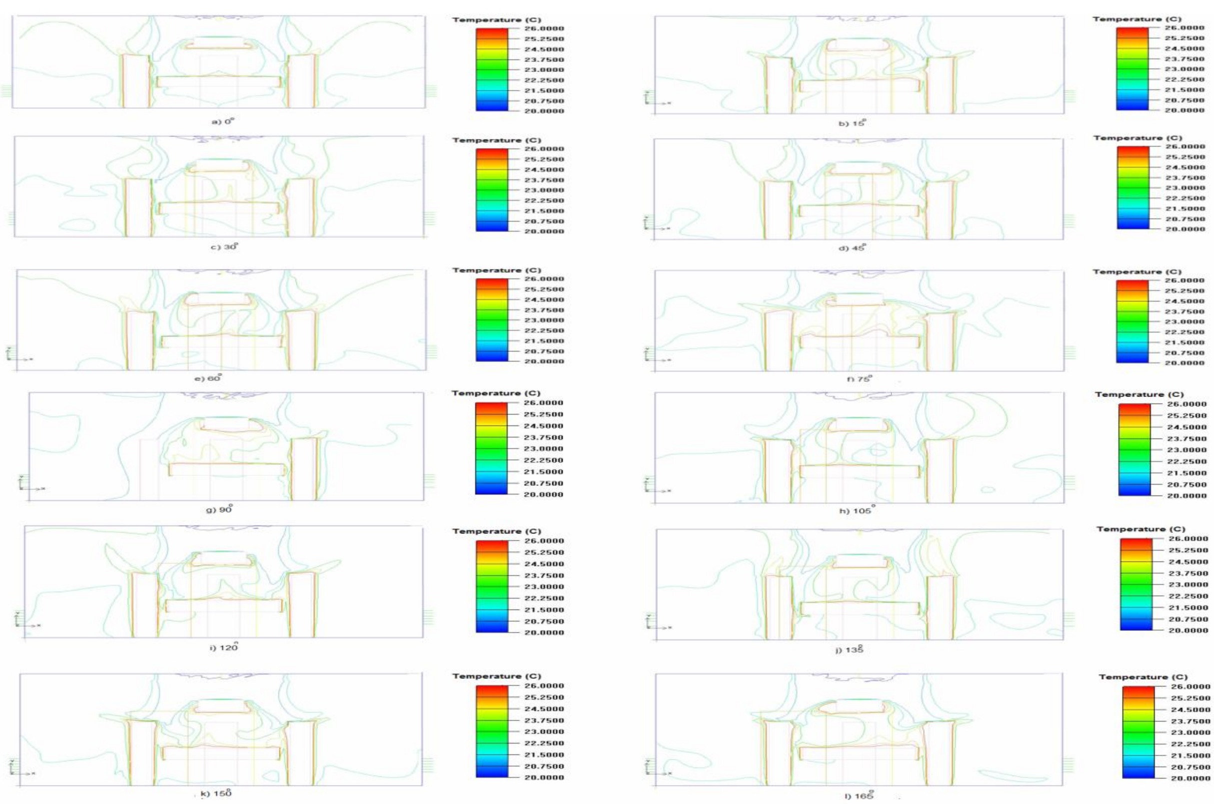

figure (13) temperature contours on z=2.15m plane

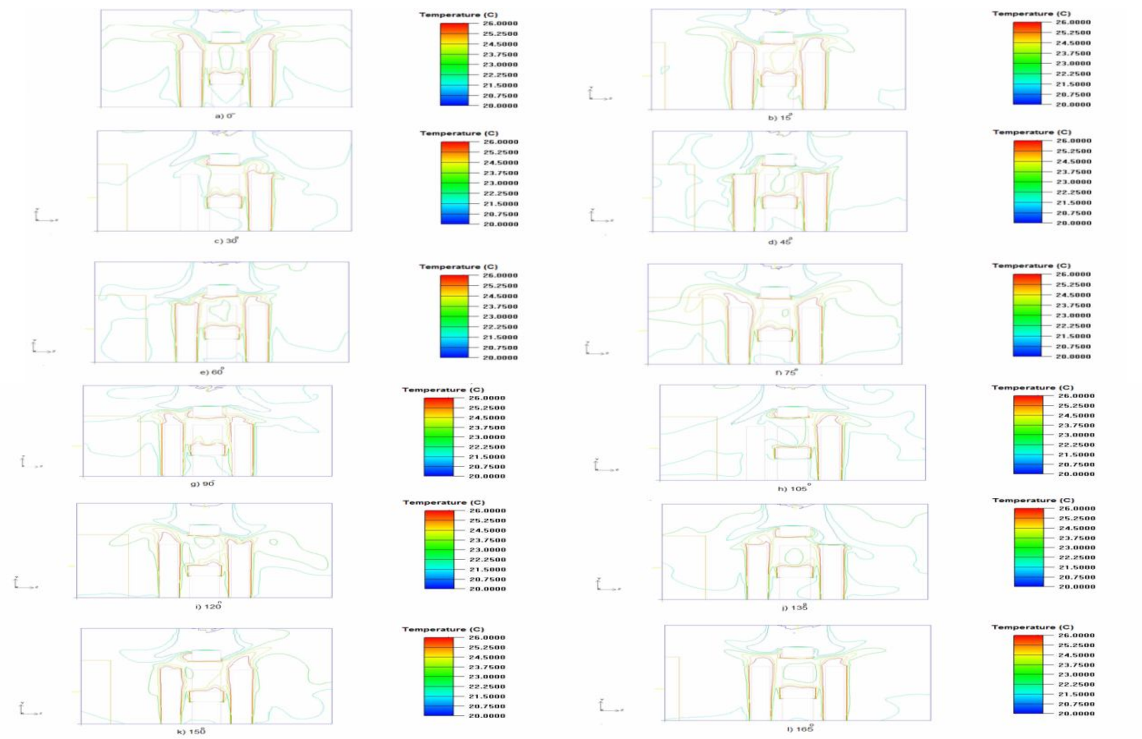

Figure (14) temperature contours on x=3.05m plane

Corelations are made for the temperature beyond patient and staff members in terms of position on the body and the door opening angle (0^o to 180^o) as follows

TABLE (3) CORELATIONS FOR TEMPERATURE

Position	correlation	Error (%)
5 cm beyond patient's body	$temperature = 24.17 + \cos(1.92 + \theta + 3.46 * \theta^2) - \cos(5.14 * x)$	6.1
5 cm beyond Staff (1) body	$temperature = 23.08 + \sin(33.52 * \theta^2) + \sin(y - 0.859 * \theta^2)$	6.8
5 cm beyond Staff (2) body	$temperature = 23.19 + y + y^2 * \cos(4.89 + 29.86 * \theta)$	5.9
5 cm beyond Staff (3) body	$temperature = 24.84 - y - 3.318 * \sin(0.8342 - y)$	7
5 cm beyond Staff (4) body	$temperature = 24.84 + y - 2.229 * \cos(y)$	6.2

4. Conclusion

Three dimensional study of uni-directional flow in an operating room with ceiling supply and side exhaust grills is studied. The effect of gradual door opening is investigated. Speed and temperature distributions are used to judge the thermal comfort. It is concluded that surgery rooms need to be pressurized to avoid back flow especially beside the exhaust grilles an over-pressurization of 25 Pa is sufficient and exhaust grilles should be elevated about 20 cm to ensure proper air flow. The uni-directional flow regime ensures a mild velocity for air inside the room (about 0.45 m/s). For the case of closed door no dead zones are observed specially inside the working zone and the gradual opening of the door causes air to move easier towards the door which causes dead zones that are gradually pronounced throughout the working zone. Recirculation greatly affects the patient when the door is opened. Also a slight recirculation is observed beyond staff members nearer to the door. Regarding thermal sensation the gradual door opening causes high temperature zones to appear which causes discomfort conditions.

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
g	Gravitational acceleration, m/s^2
h	Heat transfer coefficient, $W/(m^2\ K)$
k	Thermal conductivity of air, W/(m K)
q	Heat flux, W/m^2
q_w	Water vapour flux, kg_w/kg_a
q_c	Contaminant flux, kg_c/kg_a
T	mean temperature (with subscript), ^oC
u	Velocity in x-direction, m/s
v	Velocity in y-direction, m/s
w	Velocity in z-direction, m/s
Greek symbols	
β	Thermal expansion coefficient, K^{-1}
μ	Viscosity of air, kg/(m s)
ρ	Density of air, kg/m^3
ω	Concentration of species, kg of species/kg of mixture
Abbreviations	
ACH	Air changes per hour
AHU	Air handling unit
CFD	Computational fluid dynamics
FVM	Finite Volume Method
IAQ	Indoor air quality
HEPA	High efficiency particulate air
Subscripts	
c	Contaminant
w	Water vapor
x	x direction
y	y direction
z	z direction

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