CFD Letters www.cfdl.issres.net Vol. 5 (2) – June 2013

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

Part (II) Effect on mean age of the air and predicted mean vote distribution

Abd el Hamid Attia, Mohamed El Helw and Hebat-Allah M. Teamah*

Mechanical Engineering Department, Faculty of Engineering
Alexandria University, EGYPT
Received: 17/01/2013 – Revised 05/04/2013 – Accepted 20/04/2013

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 modeling approach. Solutions of the distribution of mean age of air and predicted mean vote are presented and discussed in this part of the paper. The simulation results show a good agreement with previous published data. Effects of door opening on thermal comfort are explored. Correlations are made for the studied parameters. The study numerically assured the bad influence of door opening on thermal comfort and air change.

Keywords: HVAC; Thermal comfort; IAQ; PMV and mean age of air.

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. Chang et al. [1] numerically investigated the effect of ventilation pattern on contaminant transport behavior in a naturally ventilated two-room building. Chang and Hu [2] numerically studied the transport mechanism of size-dependent airborne particulate matters in partitioned indoor environment. Chih-Shan Li et al. [3] carried out a series of field tests and got the bacterial and fungal concentrations in different parts of a hospital. Chow et al. [4] studied a non-standard operating room, with a supply diffuser screened with a perforated steel plate. Results showed that bacteria concentration was very sensitive to the position of lamps.

* Corresponding Author: Hebat-Allah M. Teamah Email: hebateamah@yahoo.com Telephone: +203 5021803
 PII: S2180-1363(13)51020-X

Chow and Yang [5,6] used CFD analysis to simulate contaminant dispersion supported by observations and field measurements in a case study and concluded that the application of CFD is useful to understand the adequacy of the ventilation design. Dorothea Hansen et al [7] measured bacterial and particle concentrations at the level of operative fields under laminar air flow conditions. Helmis et al. [8] presented an experimental and theoretical study on assessing the status of air quality in a dentistry clinic with respect to chemical pollutants. Jayaraman et al. [9] reported a CFD study of containment of airborne hazardous materials in a ventilated room containing a downdraft table. Khalil and Kameel [10] studied the balance between thermal comfort and air quality in healthcare facilities to optimize the indoor air quality in healthcare applications. Lu et al. [11] calculated particle trajectories using Lagrangian approach, based on Newton's 2nd Law of motion. The computational result verified the common thought that gravity has more influence on larger sized particles than on smaller ones. Memarzadeh and Manning [12] simulated contaminant deposition in an operating room using CFD air flow modeling and showed that a laminar flow condition is the best choice for a ventilation system when contaminant deposition is considered. Noie-Baghban et al [13] 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. [14] compared their measured and simulated results for indoor airflow in a single test room equipped with an internal partition. Rui et al [15] studied the airborne transmission of bacteria in two operating rooms during two surgeries. Scherrer et al [16] provided measures that are taken to ensure timely restarting of the ventilation system prior to surgery (at least 30 min before the OR is used). Son H. Ho et al [17] presented a three-dimensional analysis for thermal comfort and contaminant removal in a hospital operating room. They used PMV to judge thermal comfort. Wecxsteen et al [18] 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 position. Woods et al. [19] presented a study to identify and demonstrate control strategies that could reduce energy requirements while not producing harmful effects on the environmental quality within the operating room. Zhang Rui et al [20] focused on the airborne transmission of bacteria in two operating rooms during two surgeries in two operating rooms.

From the previous survey the thermal comfort under uni-directional flow with the effect of door opening needs to be more investigated so the main objective of the present work is to study the air distribution in an operating room with door opened successively (15^{o} increment) and its effect on IAQ parameters.

2. Numerical details

2.1. Governing equations and solver details

The studied model and numerical simulation and solver settings with the same boundary conditions as those imposed in part (I) of the paper.

2.2. Validating the problem code

The code was validated by comparing with Son el al [17] with their same model. The comparison showed good agreement with past results as shown in table (1) with maximum deviation 8.2%

3. Results and discussion

The set of coupled equations presented in the previous section are solved numerically. Results in this part of the paper are displayed for mean age of air inside the operating room and the predicted mean vote (PMV) which is computed as an ASHRAE scale combining all IAQ parameters. The index scale indicates +3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool,

-2 cool and -3 cold. The results are depicted on mid planes in x and z directions and 5 cm beyond patient and staff members to judge thermal comfort.

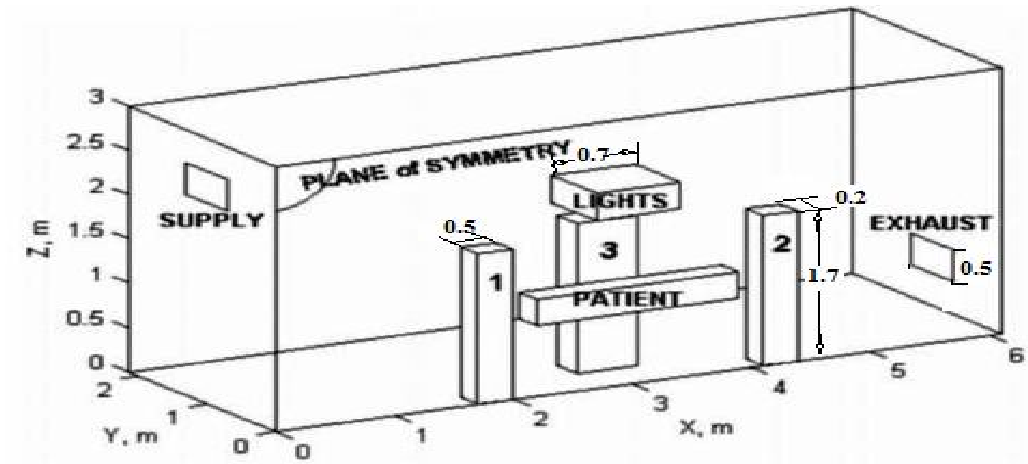

Figure (1) previous work to be compared with

TABLE (1) COMPARISON OF PRESENT CODE WITH SON ET AL [17]

Run	Average predicted mean vote for the present work	Average predicted mean vote for the previous work	Percentage deviation
- supply grilles shifted 0.5 m from centerline - - return grilles shifted 0.5 m from centerline	-0.58	-0.54	7.4 %
- supply grilles shifted 0.5 m from centerline - return grilles shifted 1 m from centerline	-0.54	-0.57	5.3 %
- supply grilles shifted 0.5 m from centerline - return grilles shifted 1.5 m from centerline	-0.62	-0.6	3.3 %
- supply grilles shifted 1 m from centerline - return grilles shifted 0.5 m from centerline	-0.56	-0.52	7.6 %
- supply grilles shifted 1 m from centerline - return grilles shifted 1 m from centerline	-0.49	-0.53	7.5 %
- supply grilles shifted 1 m from centerline - return grilles shifted 1.5 m from centerline	-0.58	-0.54	7.4 %
- supply grilles shifted 1.5 m from centerline - return grilles shifted 0.5 m from centerline	-0.54	-0.5	8 %
- supply grilles shifted 1.5 m from centerline - return grilles shifted 1 m from centerline	-0.53	-0.49	8.2 %

$$PMV = [0.303\exp(-0.036M) + 0.028]x\{(M - W) - 3.96x10^{-8}f_{cl}[(T_{cl} + 273.15)^4 - (T_r + 273.15)^4] - f_l h_{conv}(T_{cl} - T_a) - 3.05[5.733 - 0.007(M - W) - 0.001p_w] - 0.42[(M - W) - 58.15] - 0.0173M(5.867 - 0.001p_w) - 0.0014M(34 - T_a)] \quad (8)$$

Where

$$T_{cl} = 35.7 - 0.0275(M - W) - R_{cl}\{3.96x10^{-8}f_{cl}[(T_{cl} + 273.15)^4 - (T_r + 273.15)^4] + f_{cl}h_{conv}(T_{cl} - T_a)\} \quad (9)$$

$$h_{conv} = \begin{cases} 2.38(T_{cl} - T_a)^{0.25} & 2.38(T_{cl} - T_a)^{0.25} > 12.1\,v^{0.5} \\ 12.1\,v^{0.5} & 2.38(T_{cl} - T_a)^{0.25} > 12.1\,v^{0.5} \end{cases} \quad (10)$$

$$f_{cl} = \begin{cases} 1 + 0.2I_{cl} & I_{cl} \le 0.5\ clo \\ 1.05 + 0.1I_{cl} & I_{cl} > 0.5\ clo \end{cases} \quad (11)$$

$$R_{cl} = 0.155I_{cl} \quad (12)$$

Where, L is the thermal load on the body (W/m^2); M the metabolic rate of human body (W/m^2); W the rate of mechanical work accomplished (W/m^2); t_a the air temperature; t_r the mean radiant temperature; f_{cl} the clothing area factor , dimensionless; t_{cl} the mean temperature of the outer surface of the clothed body; h_c the convective heat transfer coefficient (W/m^2C). p_a the water vapor pressure in ambient air (kPa)., t_{cl} clothing temperature.

3.1. Effect of door opening on mean age of the air contours

Mean age of air decreases on the upper limbs of the patient's body till door is opened 90^o but further opening reverses the situation as shown in figure (2).

Mean age of air increases slightly on staff upper limbs but increases obviously on their lower limbs as shown in figure (3), (4), (5) & (6). These causes contradict in thermal sensation. Figures (7) & (8) demonstrate the increase of the mean age of air on the mid-planes of the room which is understood by the formed recirculation that forms an obstacle to the air throughout the room

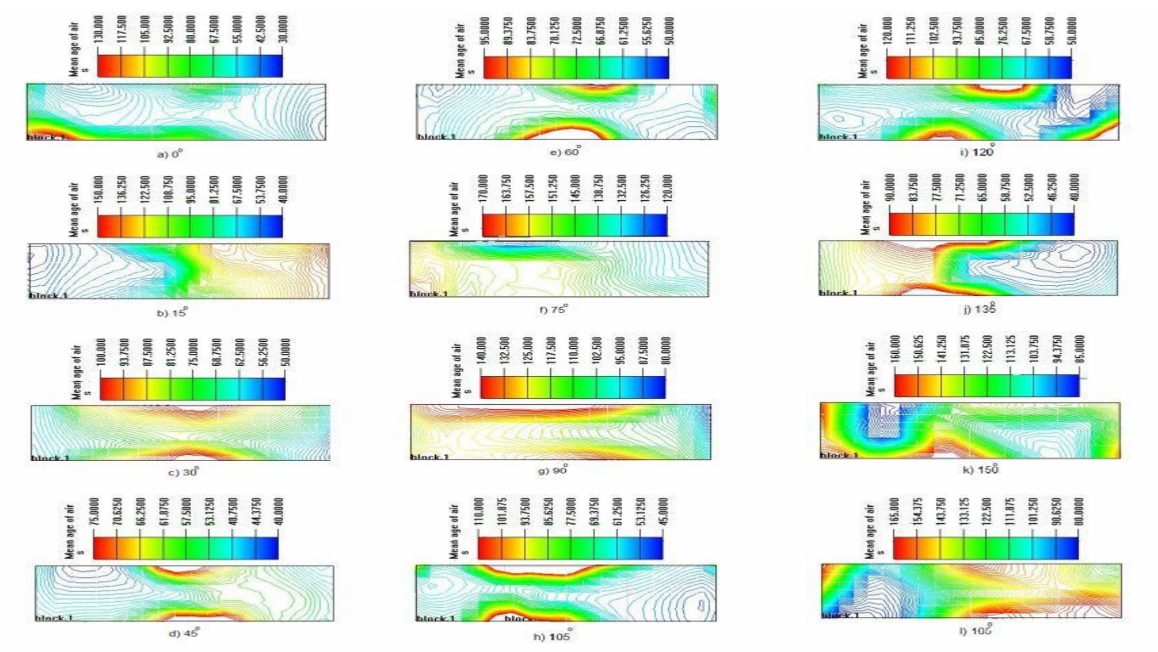

Figure (2) mean age of air 5 cm beyond patient body

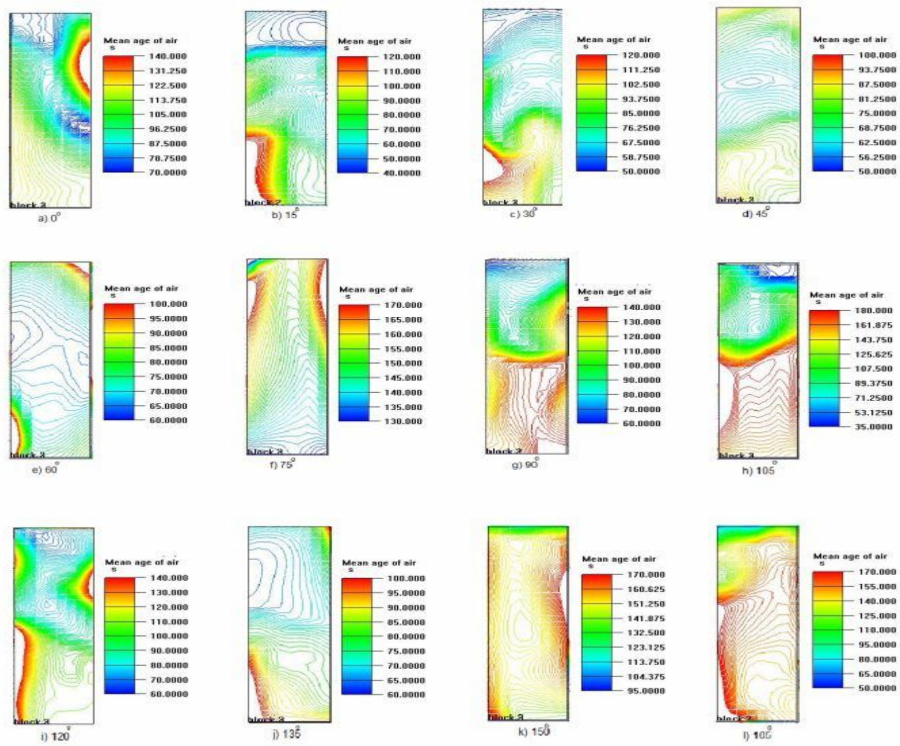

Figure (3) mean age of air 5 cm beyond staff (1) body

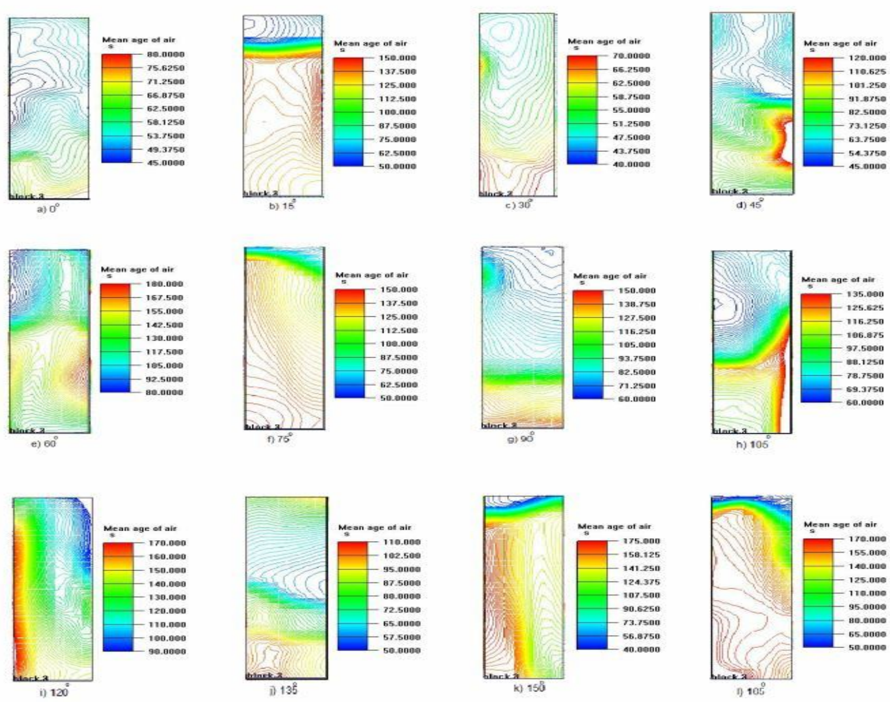

Figure (4) mean age of air 5 cm beyond staff (2) body

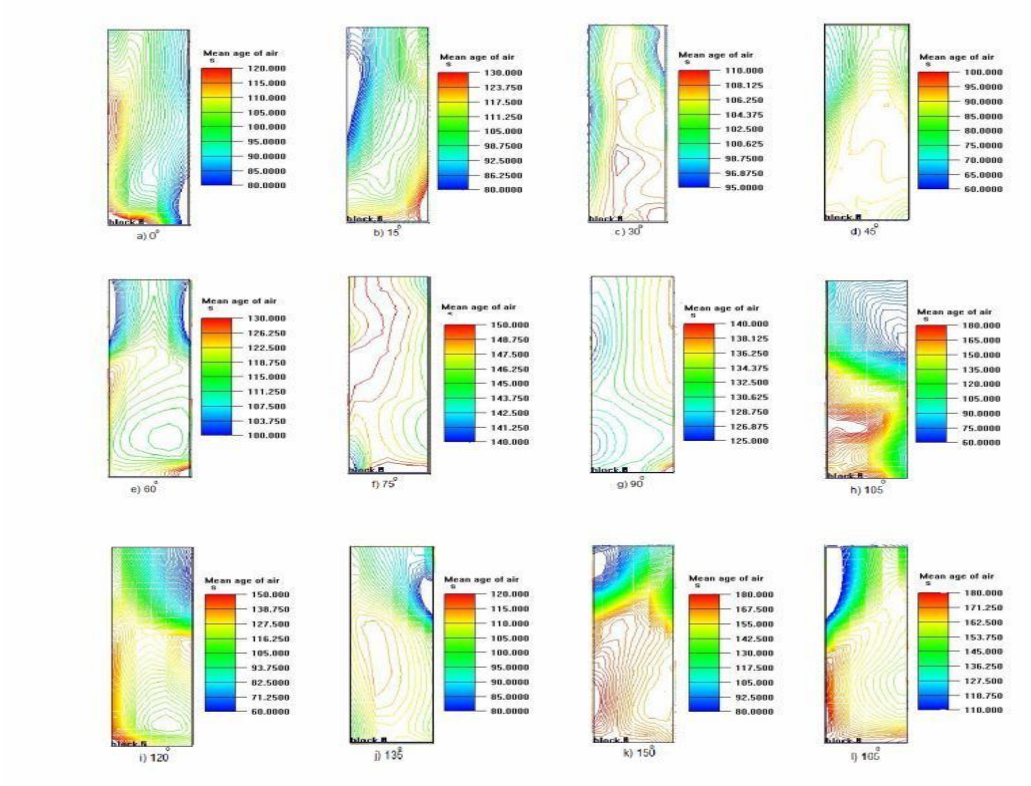

Figure (5) mean age of air 5 cm beyond staff (3) body

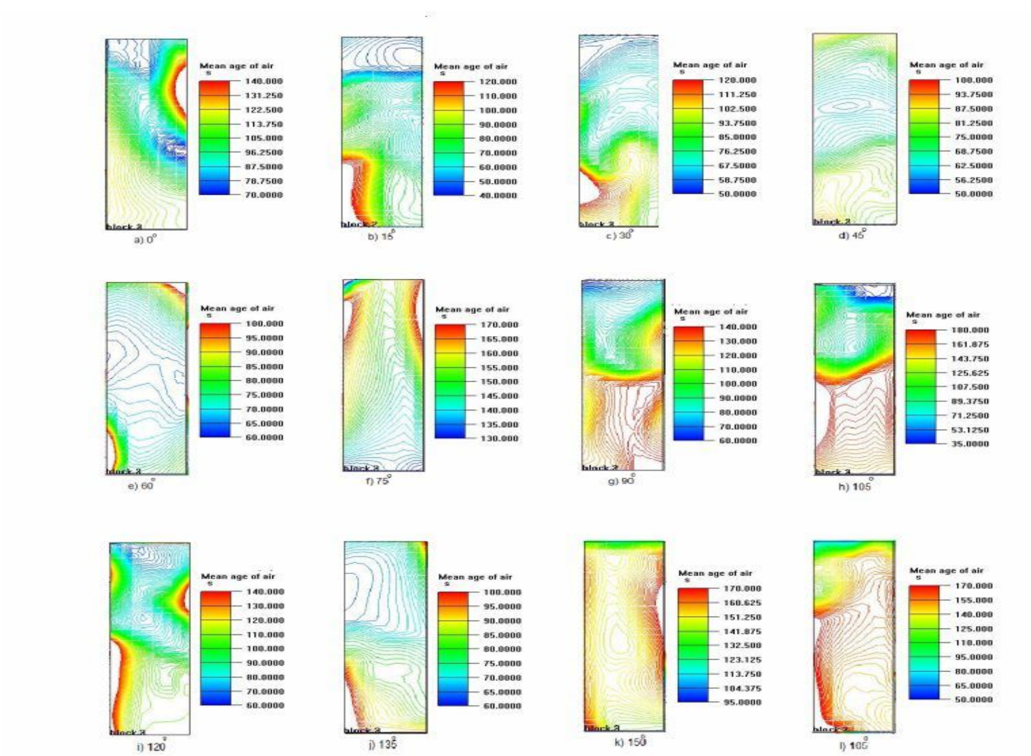

Figure (6) mean age of air 5 cm beyond staff (5) body

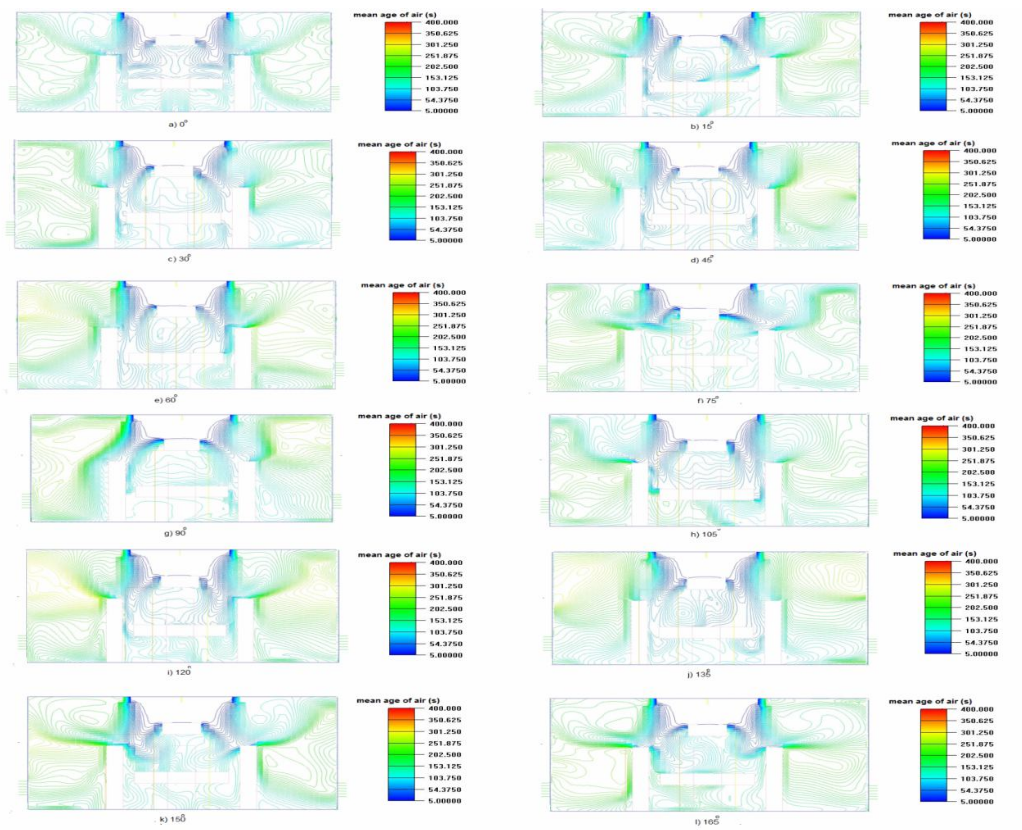

Figure (7) mean age of air on z=2.15m plane

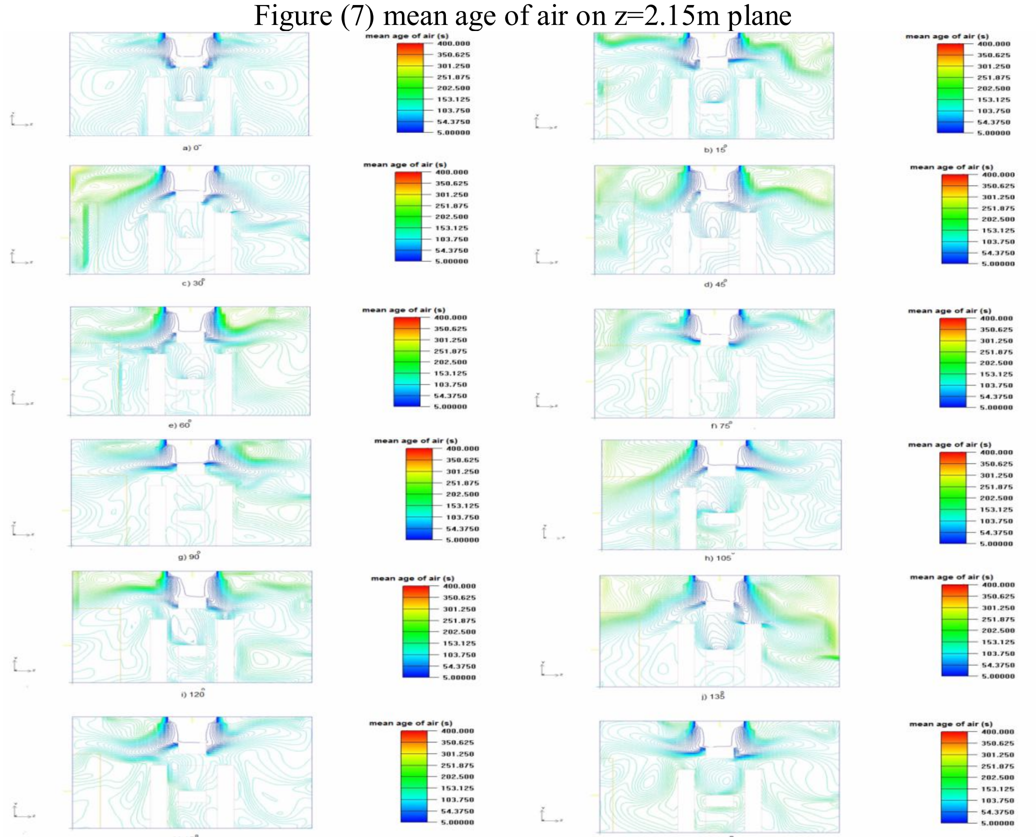

Figure (8) mean age of air on x=3.05m plane

3.2. Effect of door opening on PMV contours

The overall PMV in the room is clearly shown in figures (9) and (10) where the cold zones propagate through the lower portion of the room. hot humid zones moves towards the patient lower limbs on opening the door up to 75^o , thereafter the reverse situation takes place. Hot humid zone remains on the upper portion of staff (1) with gradual door opening whereas slightly cooler and less humid feeling affect the lower portion of his body. Hot and humid zone moves towards the middle portion of staff (2) till the door is opened 90^o by further door opening this zone moves towards his upper limbs. Hot and humid air propagates through the upper limbs of staff (3) till the door is opened to 90^o but further opening causes the hot humid zone to propagate through lower limbs with slight cooling of upper limbs. Slightly cool and less humid zone affects the upper limbs of staff (4) till 90^o door opening then hot humid zone propagates gradually through upper limbs, whereas lower limbs are slightly affected in general .

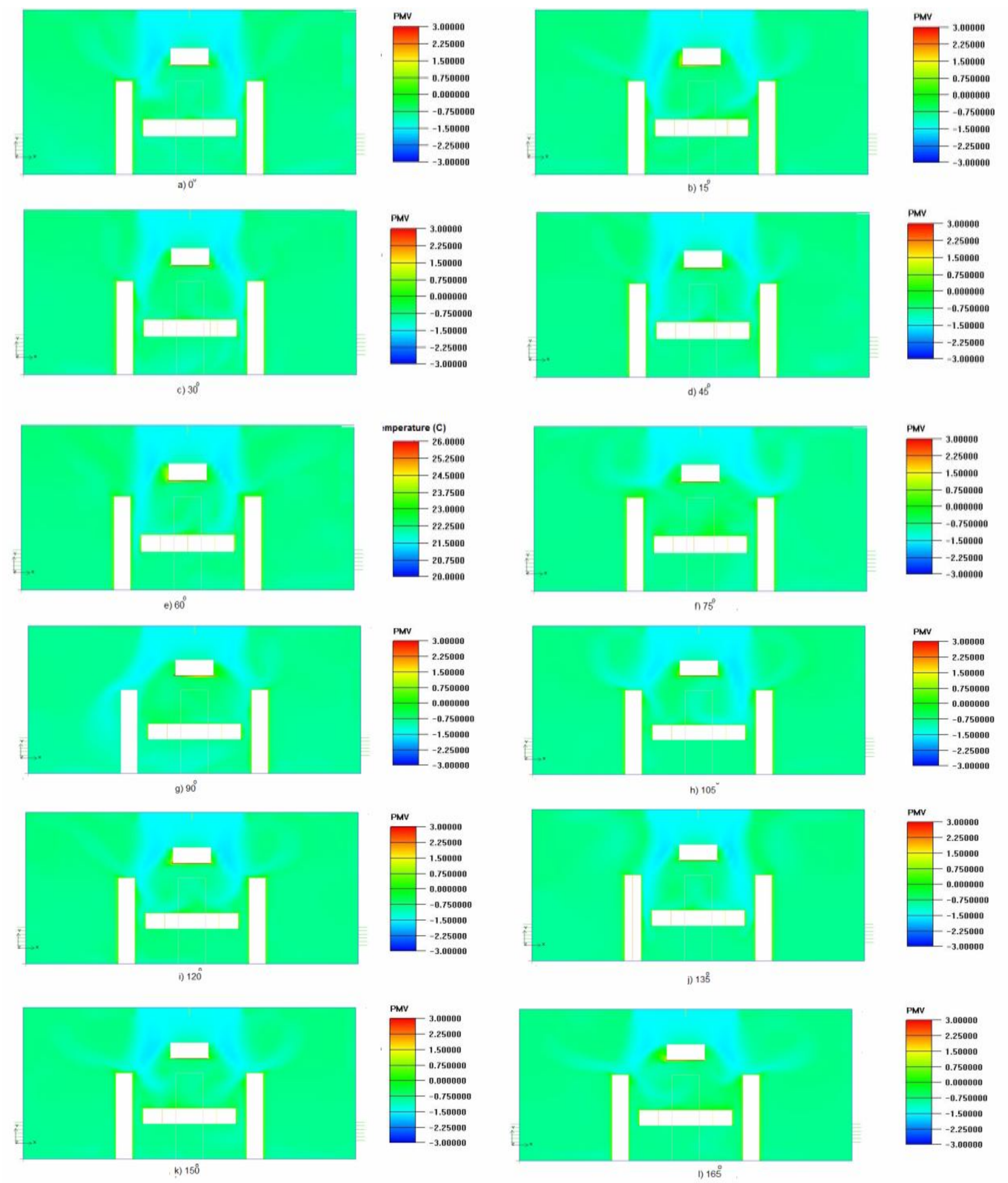

Figure (9) PMV contours on z=2.15m plane

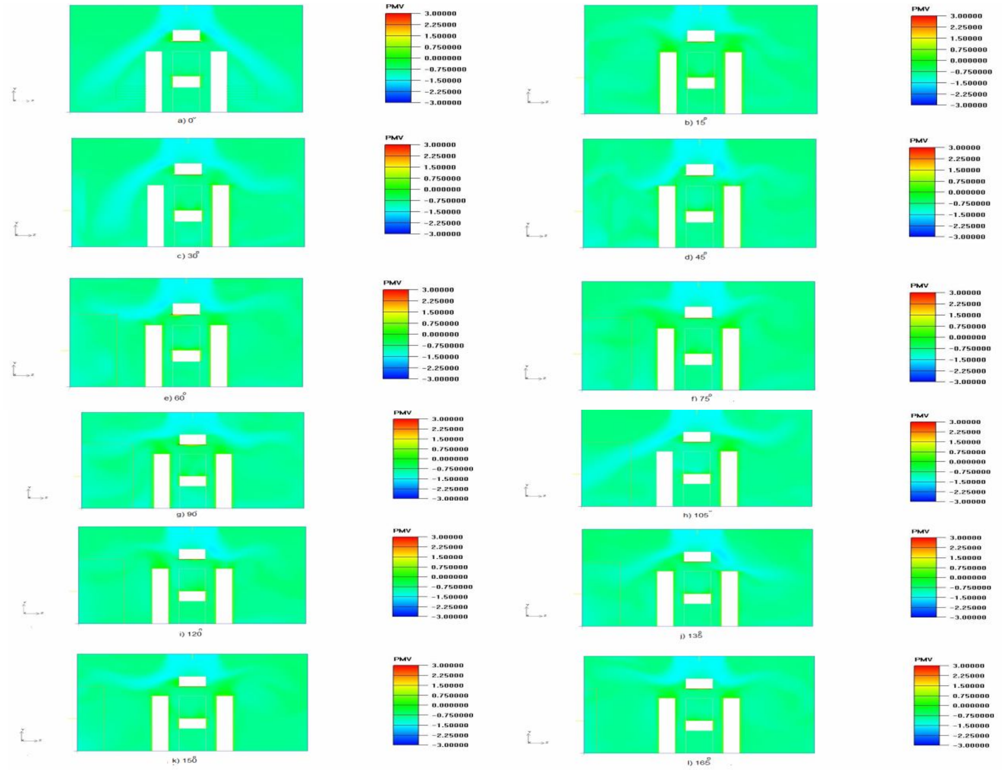

Figure (10) PMV contours on x=3.05m plane

Correlations are obtained for both mean age of air and predicted mean vote in terms of position on the body and door opening angles (0^o to 180^o) as in table (2)

TABLE (2) MEAN AGE OF AIR AND PREDICTED MEAN VOTE CORRELATIONS

	Position	correlation	error
Mean age of air	5 cm beyond patient's body	$mean\ age\ of\ air = -108.3/(\sin(-265.1*\theta^2) - 1.775)$	6.3%
	5 cm beyond Staff (1) body	$mean\ age\ of\ air = 122.2 - 19.29*y - 44.82*\cos(0.9757 + \theta^2 - 74.05*\theta)$	6.6%
	5 cm beyond Staff (2) body	$mean\ age\ of\ air = 112.4 - 21.98*y - 41.26*\cos(4.545*\theta + \theta^2)$	5.5%
	5 cm beyond Staff (3) body	$mean\ age\ of\ air = 106.3 + 0.3755*\theta*\sin(-2.554*\theta^2))$	7.3%
	5 cm beyond Staff (4) body	$mean\ age\ of\ air = 89.57 + 0.3643*\theta + 24.86*\cos(-17.52*\theta) - y$	6.1%
	Position	**correlation**	**error**
Predicted mean vote	5 cm beyond patient's body	$PMV = -0.8137 - 0.2283*\cos(42.41*\theta^2 - 249.3*\theta))$	5.1%
	5 cm beyond Staff (1) body	$PMV = 0.1585*y^2*\cos(1.172 + 0.1544*\theta) - 0.7796$	6.3%
	5 cm beyond Staff (2) body	$PMV = 0.1571*y^2*\cos(57.5*\theta) - 0.7423$	5.5%
	5 cm beyond Staff (3) body	$PMV = 0.1534*y*\sin(\theta + 2.335*\cos(\theta)) - 0.8495$	7.4%
	5 cm beyond Staff (4) body	$PMV = 0.8341*y - 0.7799 - \sin(0.8707*y)$	4.2%

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. Mean age of the air and PMV are used to judge the thermal comfort in this part of the paper. Correlations are made for the studied parameters in the modeled room. It is seen that the gradual door opening causes an increase in the mean age of the air on the lower limbs of patient and staff member relative to the upper limbs which contradicts comfort conditions and the gradual door opening causes hot and humid zones to propagate inside the room which deviates from the desirable thermal sensation which assures that doors must be closed throughout the time of operation.

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
f_{cl}	Ratio of clothed surface area to nude surface area
g	Gravitational acceleration, m/s^2
h	Heat transfer coefficient, $W/(m^2 K)$
I	Thermal resistance in ‘‘clo” units, clo (1 clo = 0.155 m^2 K/W)
k	Thermal conductivity of air, W/(m K)
K	Regression coefficients (with subscript), m^{-1}
M	Metabolic heat generation flux, W/m^2 of naked body area
q	Heat flux, W/m^2
q_w	Water vapour flux, kg_w/kg_a
q_c	Contaminant flux, kg_c/kg_a
R	Thermal resistance, m^2 K/W
T	Temperature; 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
W	External work, W/m^2 of naked body area
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
Common 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
PMV	Predicted mean vote
Subscripts	
C	Contaminant
Conv	Convective
Cl	Clothing
R	Radiant
Ref	Reference
s	Saturated
w	Water vapor
x	x direction
y	y direction
z	z direction

REFERENCES

[1] T.J. Chang, H.M. Kao, Y.F. Hsieh, Numerical study of the effect of ventilation pattern on coarse, fine, and very fine particulate matter removal in partitioned indoor environment, Journal of the Air and Waste Management Association 57 (2007) 179–189.

[2] T.J. Chang, T.S. Hu, Transport mechanism of airborne particulate matter in partitioned indoor environment, Building and Environment 43 (2008) 886–895.

[3] Li Chih-Shan, Hou Po-An. Bioaerosol characteristics in hospital clean rooms. The Science of the Total Environment 2003;305:169–76.

[4] Chow Tin-Tai, Yang Xiao-Yu. Performance of ventilation system in a non-standard operating room. Building and Environment 2003;38:1401–11.

[5] T.T. Chow, X.Y. Yang, Ventilation performance in operating theatres against airborne infection: review of research activities and practical guidance, Journal of Hospital Infection 56 (2004) 85–92.

[6] T.T. Chow, X.Y. Yang, Performance of ventilation system in a nonstandard operating room, Building and Environment 38 (12) (2003) 1401–1411.

[7] Dorothea Hansen, Carsten Krabs, Daniel Benner,Andreas Brauksiepe, Walter Popp, Laminar air flow provides high air quality in the operating field even during real operating conditions, but personal protection seems to be necessary in operations , Int. J. of Hygiene And Health 20 (2005) 455-466

[8] C.G. Helmis, J. Tzoutzas, H.A. Flocas, C.H. Halios, O.I. Stathopoulou, V.D. Assimakopoulos, V. Panis, M. Apostolatou, G. Sgouros, E. Adam, Indoor air quality in a dentistry clinic, Science of the Total Environment 377 (2–3) (2007) 349–365.

[9] B. Jayaraman, A.H. Kristoffersen, E.U. Finlayson, A.J. Gadgil, CFD investigation of room ventilation for improved operation of a downdraft table – novel concepts, Journal of Occupational and Environmental Hygiene 3 (11) (2006) 583–591.

[10] E.E. Khalil, R. Kameel, Requirements of air-conditioning systems' developments in hospitals and critical healthcare facilities, in: Proceedings of the Seventh Biennial Conference on Engineering Systems Design and Analysis, vol. 3, 2004, pp. 375–381.

[11] Weizhen Lu , Howarth AT, Nor A, Riffat SB. Modeling and measurement of airflow and aero particle distribution in a ventilated two-zone chamber. Building and Environment 1996;5:417–23.

[12] F. Memarzadeh, A. Manning, Comparison of operating room ventilation systems in protection of the surgical site, ASHRAE Transactions 108 (2) (2002) 3–15.

[13] S.H. Noie-Baghban, G.R. Majideian, Waste heat recovery using heat pipe heat exchanger (HPHE) for surgery rooms in hospitals, Applied Thermal Engineering 20 (14) (2000) 1271–1282.

[14] J.D. Posner, C.R. Buchanan, D. Dunn-Rankin, Measurement and prediction of indoor air flow in a model room, Energy and Buildings 35 (2003) 515–526.

[15] Z. Rui, T. Guangbei, L. Jihong, Study on biological contaminant control strategies under different ventilation models in hospital operating room, Building and Environment 43 (5) (2008) 793–803.

[16] M. Scherrer, Hygiene and room climate in the operating room, Minimally Invasive Therapy & Allied Technologies 12 (2003) 293–299.

[17] Son H. Ho, Luis Rosario, Muhammad M. Rahman (2009), Three-dimensional analysis for hospital operating room thermal comfort and contaminant removal, Applied Thermal Engineering, 29: 2080–2092.

[18] Wecxsteen H, Kastally M, Woloszyn M, Virgone J, Laporthe S. Travaux Experimentaux en vue de Valider un Code de Description des Ecoulements d'Air Interieur. Rapport final, Convention Insavalor-Air liquide, no 6715, 2000.

[19] J.E. Woods, D.T. Brayman, R.W. Rasmussen, P.E. Reynolds, G.M. Montag, Ventilation requirements in hospital operating rooms. Part I: Control of airborne particles, ASHRAE Transactions 92 (2) (1986) 396–426.
[20] Zhang Rui, Tu Guangbei, Ling Jihong, Study on biological contaminant control strategies under different ventilation models in hospital operating room, Building and Environment 43 (2008) 793–803