Modeling and Experimental Investigation of Laminar Ceiling Air Distribution System for Operating Room in Merjan Teaching Hospital

Isam Mejbel Abed[1,*] & Ruqaia Amer[2]

[1]Department of Mechanical Engineering, College of Engineering, University of Babylon, Babylon, Iraq
[2]Air Conditioning and Refrigeration Techniques Engineering Department, Al-Mustaqbal University College, Babylon, Iraq
*E-mail: eng.isam.m@uobabylon.edu.iq

Abstract. Room air distribution in operating rooms is critical to successful surgical treatment. The present study investigated the effects of the location of the air supply and exhaust grills on the air movement and air parameters inside an operating room. This paper presents an experimental and numerical analysis of air distribution in the operating room. The experimental work was conducted in an operating room in Merjan Teaching Hospital in the city of Babylon. Air was supplied from one square plenum box located in the middle of the ceiling, while air was exhausted through eight grills: large exhaust grills in the four upper corners and small exhaust grills in the four lower corners. In the theoretical work, a model of the operating room was developed and two cases were analyzed using the FLUEN 6.3.26 software program. The first case included all eight exhaust grills, while the second case included only the four lower exhaust grills. The ceiling system gave good ventilation for air distribution inside the operating room. There was no clear effect of the small exhaust grills located in the upper corners of the operating room. The height of the ceiling room is an effective factor in air distribution.

Keywords: *airflow distribution; air parameters ceiling laminar flow system; CFD; experimental work; operating room; simulation.*

1 Introduction

The effect of air distribution for ventilation is important inside operating rooms. The design uses a full laminar air flow ceiling system. Many researchers have dealt with experimental work, but only few of them have dealt with validation using a numerical model. Experimental data for CFD validation must contain particular information on air flow and thermal parameters. Murakami, *et al.* made a comparison between the results of turbulence modeling and measurements for different ventilation configurations [1]. Chen compared two-equation k–models with experimental results. They found that the RNG k–model worked better than the standard k-e model for simulating displacement

Received September 24th, 2018, Revised November 26th, 2018, Accepted for publication December 12th, 2018.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2018.50.6.9

airflow [2]. The same conclusion was obtained by using Commercial Code CFX model.

The simulation results were found to produce good quality when compared with those of the mathematical theory. Although the advantage of an RNG model is not obvious for modeling airflow in operating rooms, the RNG model performed slightly better in predicting buoyancy driven displacement flow [3]. On the other hand, Alwan and Abid Ali [4] examined the validity of air distribution in an operation room. The air was supplied to the room through grilles and it was exhausted through grills in the sidewalls. In addition, various air distribution systems inside the operation room were examined by locating the inlet at the upper part of a sidewall, while the exhaust grilles were located in the lower part of the opposite sidewall. The air temperature and relative humidity in the surgical zone were 21.3 °C and 49.3% respectively. Meanwhile, the values from the experimental work were 23.6 °C and 45.3%. These values in both operation rooms were within the range suitable for surgical conditions. Honglu analyzed a ceiling ventilation system in an office room by conducting full-scale measurements inside a climate chamber [5]. Lstiburek measured local mean air age, ventilation air distribution and air change rate for two cases of operation rooms. It was found that a laminar air flow diffuser could take out the air at optimal velocity [6].

Medhat, *et al.* measured airflow patterns, velocity, and temperature profile inside an operating room with a low ceiling. The air flow was a laminar flow. The investigated design parameters were the effect of the locations of the inlet and outlet slots as well as the hang partition, while the operating parameters were the heat source and Reynolds numbers with a wide range. The results represented the used inlet air supplied from the ceiling, which exited from two grills in the sidewalls near the floor if the space was higher than 3 m [7]. Esam and Ruqaia investigated the airflow distribution in an operating room for two cases experimentally as well as numerically. Air was exhausted from grills in four corners. In the numerical work, a model of the experimental operating room was developed. A curtain air system that was used, giving better ventilation than a laminar air flow system [8].

In this study, field tests were carried out in an operation room in Merjan Teaching Hospital in Babylon. The CFD simulation technique was applied to survey airflow characteristics based on the field-test data. The CFD simulation results were compared and analyzed with the field test data representing air velocity, temperature and relative humidity.

2 Experimental Work

The experiment was conducted in an operating room in Merjan Teaching Hospital in the city of Babylon, as shown in Figure 1.

Figure 1 Operating room Merjan Teaching Hospital.

Fresh air entered into the operating room through one square plenum box located in the middle of the ceiling. Air was exhausted through eight grills in each corner of the operating room: small grills were placed in the four upper corners, while large grills were placed in the four lower corners at a height of around 0.30% from the ground. The patient bed was located in the middle of the room under the plenum box. A schematic diagram of the operating room is shown in Figure 2 and the dimensions of the operating room and all parts are shown in Table 1.

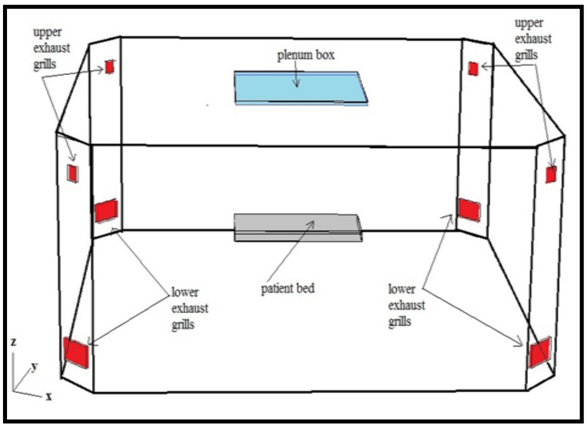

Figure 2 Schematic diagram of the operating room.

Table 1 Dimensions of operating room with all parts.

Part	Dimensions
Operating room	(7.10 × 7.10× 3) m
Plenum box	(2 × 2) m
Upper grill (×4)	(18 × 18) m each
Lower grill (×4)	(48× 25) m each
Patient bed	(2 × 0.75) m

Four air parameters were studied. The experimental measurements consisted of air velocity measurement by using a hot film air mass meter, type HFM5, relative air humidity measurement by using an analog, and air temperature measurement by using NTC sensors.

The LABVIEW program was used for directed measurement to obtain and present the results. The experimental work was done using fifteen sensors for velocity and temperature, and seven sensors for pressure and relative humidity. The measurements were done at three levels inside the operating room: (1, 1.5 and 2) m from ground level at different locations, as shown in Figure 3.

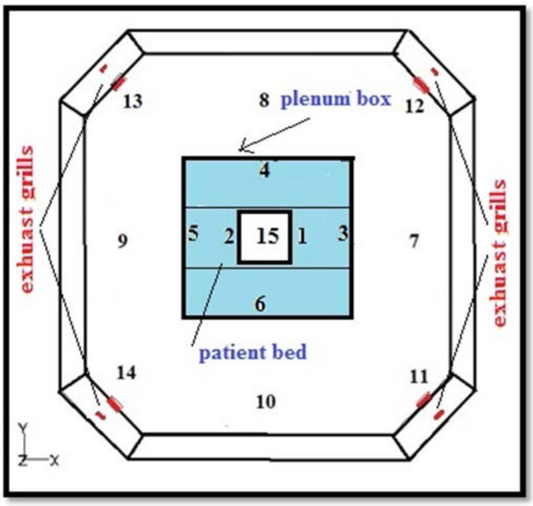

Figure 3 Top view of the operating room with the locations of the sensors.

3 Numerical Simulation (CFD)

For the numerical simulation, the FLUENT 6.3.26 software program was used to model the operating room and to study the air distribution and the air parameters inside the operating room. The standard k–ε turbulence model is more usable for airflow prediction due to the relatively low level of turbulence

[9]. The dimensions of the operating room were (7.10 × 7.10 × 3) m. The model was draw by Gambit and the mesh type was triangular and the volume mesh T-grid) [10].

3.1 Initial and Boundary Conditions

The initialization of the model is essential for convergence. If the first conditions are poor, then it takes longer to converge, or it may even result in divergence. For the present work, the initial conditions were computed from the inlet (supply). The boundary conditions are shown in Table 2 [11]. In the numerical work, the differences between two exhaust grill configurations were determined, as shown in Table 3.

Table 2 Boundary conditions of operating room.

Part	Type of boundary condition	Air temperature (K)	Air velocity (m/s)	Relative air humidity (%)
Plenum box	Velocity inlet	293	0.4	55
Exhaust grills	Outflow	60 % of air exhausted from lower grills and 25% air exhausted from upper grills		

Table 3 Difference between both cases.

Case	Exhaust grills
Case1	Eight grills Four large grills in lower corners Four small grills in upper corners
Case2	Only four large grills located in the lowercorners

4 Results and Discussion

4.1 Experimental Result

The experimental results are divided into three parts. Figure 4 represents the air velocity for three points located under the plenum box (1, 2, and 15) at three levels. It was observed that the velocity decreased from the top of the room, where the source of the air supply was located, to the bottom until reached the lowest value, approaching 0.04 m/s above the patient bed at level (z = 1 m). Meanwhile, the temperature increased from the top to the bottom, as shown in Figure 5. Figure 6 shows the distribution of the relative air humidity for the same points at the same levels. The maximum value of humidity measured at level (2 m) reached more than 46% as a result of being closer to the source of the air supply, while the lowest value of approximately 44% was at level (1 m) above the patient bed.

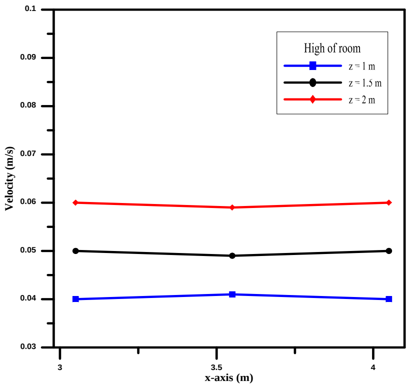

Figure 4 Air velocity distribution at three levels above the patient bed.

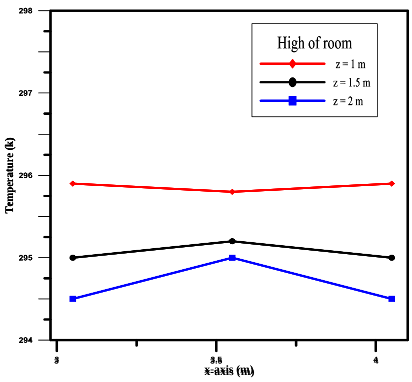

Figure 5 Temperature distribution at three levels above the patient bed.

Figure 7 represents the absolute air pressure. This is a positive pressure with a small difference compared to the pressure inside the operating room, between (108-109) Kpa. This positive pressure occurred due to exhaustion of 85% of the supplied air. Figure 8 shows a vector map of the air velocity for the section located in the middle of the operating room, crossing the patient bed at three levels. This section gives an idea of how the velocity is distributed in different zones inside the operating room. It was observed that the velocity decreased from the top of the room to the bottom for the area under the plenum box. Figure 9 shows a contour map of the temperature for the same section inside the operating room. It can be seen that the highest temperature was at level (2 m) over the patient bed under the plenum box due to being closer to the source of air supply. The highest temperature was at level (2 m) in a region far removed from the patient bed and the plenum box because the hot air went up to the upper part of the room due to the greater weight of hot air. The temperature range for this section was (294.5-297) K.

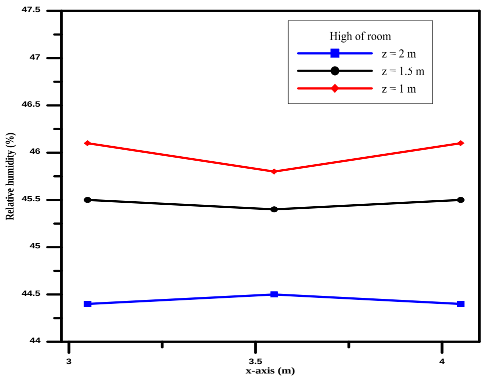

Figure 6 Relative air humidity distribution at three levels above the patient bed.

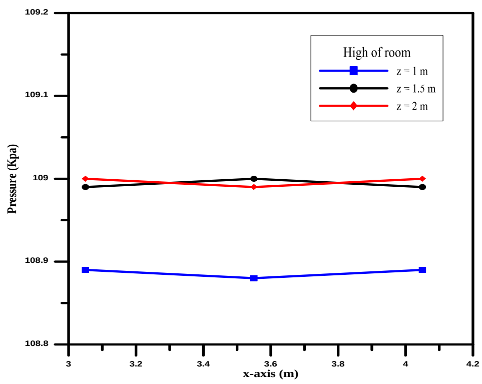

Figure 7 Absolute air pressure distribution at three levels above the patient bed.

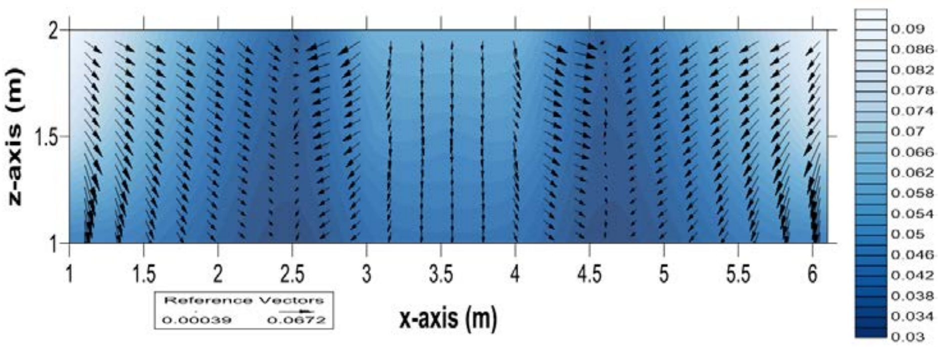

Figure 8 Vector map of air velocity (m/s).

Figure 10 shows a contour map of the relative air humidity for the same section. Relative humidity is a function of temperature so it can be seen that it decreased from (47-42)% from the top of the room to the bottom in the region under the plenum box, the opposite to what happened with the temperature. Figure 11 shows a contour map of the air pressure for the same section. It can be seen that the air pressure inside the operating room was higher than the atmospheric pressure at approximately (108 Kpa) due to good sealing of the operating room.

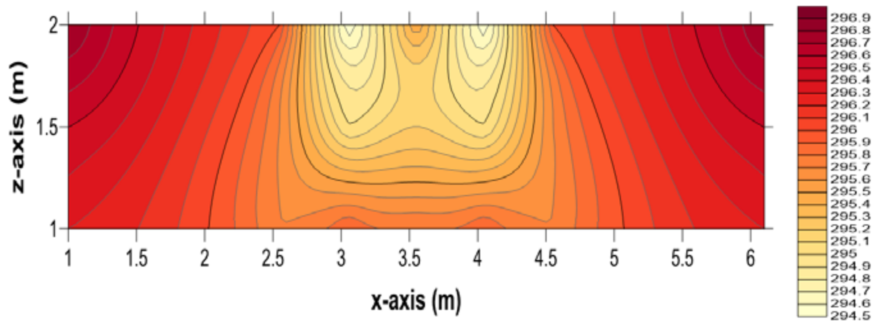

Figure 9 Contour map of air temperature (K).

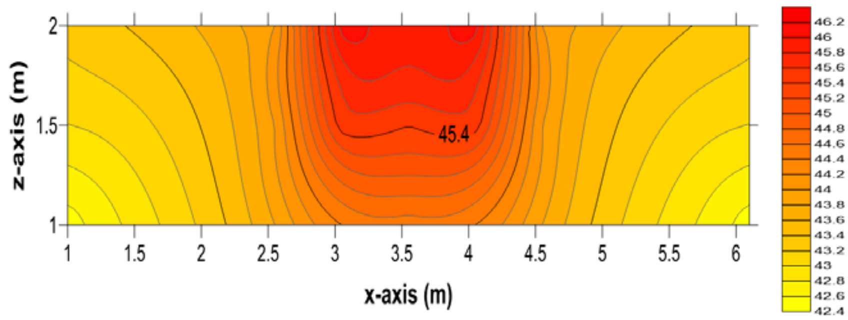

Figure 10 Contour map of relative air humidity (%).

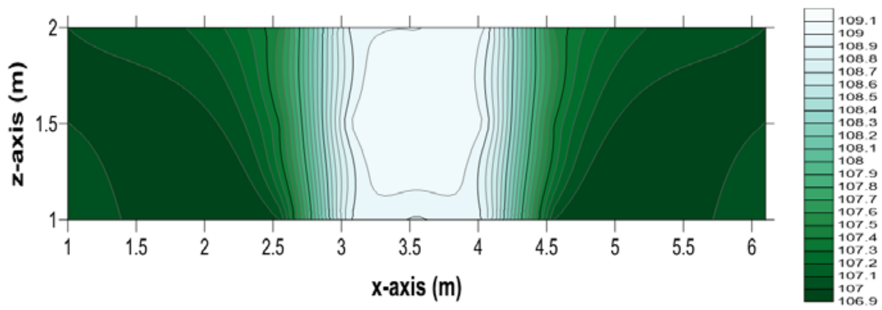

Figure 11 Contour map of absolute air pressure (Kpa).

4.2 Numerical Results

The vector map of the air velocity shows the magnitude and direction of the velocity in different regions in the operating room and the air flow path starting from the supply region on the ceiling to the lower regions. This can be seen in Figures 12 and 13, which represent the velocity vector for the same plane for both cases of the experiment. There was no clear difference in air distribution for this plane between the two cases. Also, a good velocity range was observed for this vector. Figures 14 and 15 show contour maps of the air temperature for Case 1 and Case 2 for the same plane inside the operating room. It can be seen that the air temperature increased from the top of the room, under the plenum box, to the bottom, near the patient bed. There was no large difference in temperature distribution between both cases. The temperature range, from 292 K to 300 K, was the same in both cases.

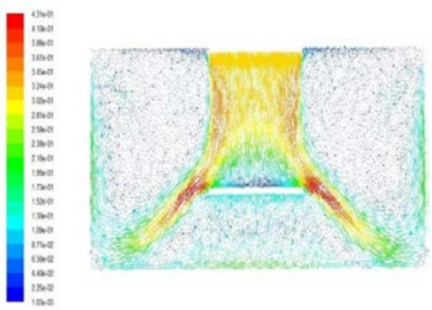

Figure 12 Contour map of the air velocity vector for (Case 1).

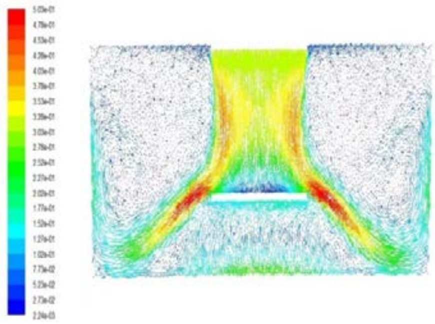

Figure 13 Contour map of the air velocity vector for (Case 2).

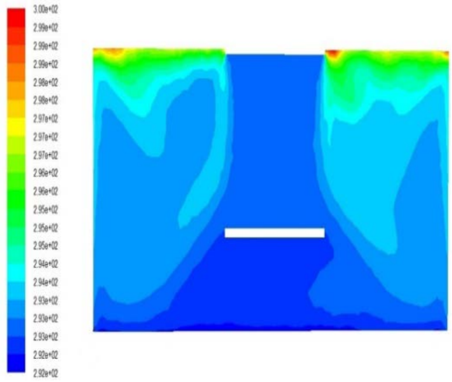

Figure 14 Contour map of the air temperature distribution for (Case 1).

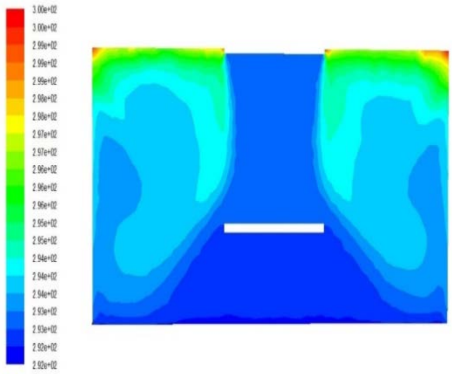

Figure 15 Contour map of the air temperature distribution for (Case 2).

Figures 16 and 17 show contour maps of the relative air humidity for Case 1 and Case 2 for the same plane inside the operating room. It can be seen that the relative air humidity decreased from the top of the room, under the plenum box, to the bottom, near the patient bed. In both cases, there was no large difference in relative air humidity distribution, especially in the patient region. There was little difference in air humidity between both cases, where the humidity in Case 1 was lower due to air being exhausted from both top and bottom grills. The opposite was the case in Case 2, where the air was withdrawn from the bottom grills only.

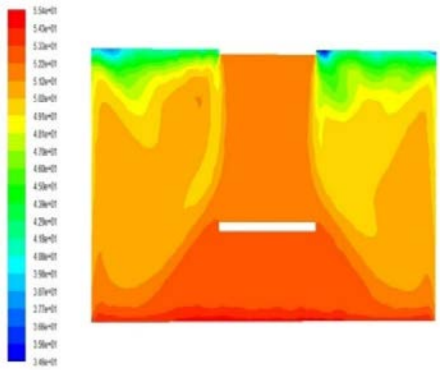

Figure 16 Contour map of the relative air humidity for Case 1 (%).

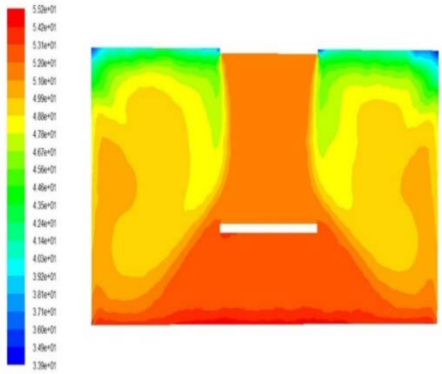

Figure 17 Contour map of the relative air humidity for (Case 2).

Figures 18 and 19 show a vector map of the air velocity for the plane crossing the operating room from the back corner to the front corner for both cases in order to show the air velocity vector for both the inlet and exhaust regions of the operating room. In Case 1, the highest value of velocity was in the exhaust regions. In addition, the upper grills exhausted a small amount of air and did not have a large effect on the air flow path, especially in the region above the patient bed.

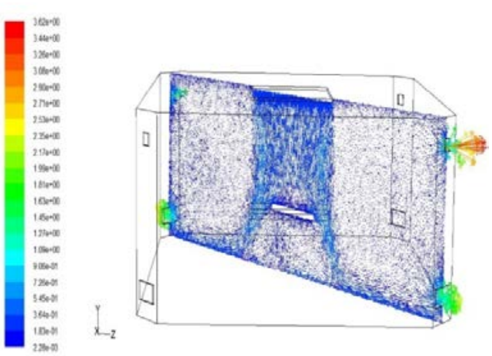

Figure 18 Contour map of the air velocity vector for (Case 1).

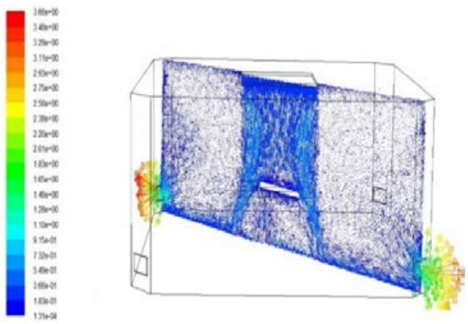

Figure 19 Contour map of the air velocity vector for (Case 2).

A vector map of air velocity for the whole operating room in both cases and take can be seen in Figure 20 and Figure 21. In Case 1, the highest air velocity was at the upper exhausted grill due to its small area, while in Case 2 it was at the lower exhaust grills due to the absence of the upper grills. It can be seen that the height of the room is suitable, where the velocity of the air coming from the plenum box above the patient bed is near zero.

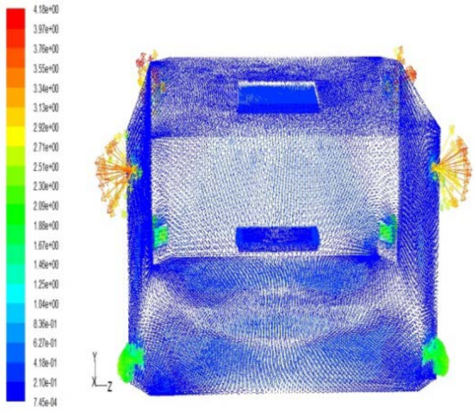

Figure 20 Contour of the air velocity vector of the whole operating room for (Case 1).

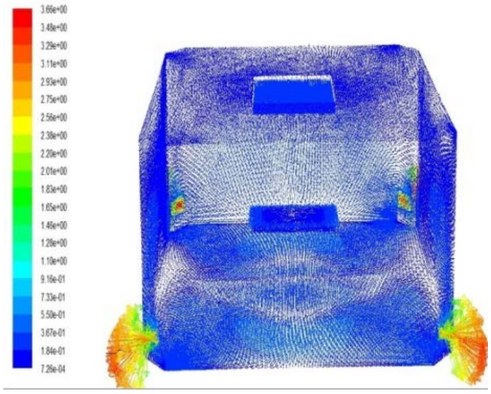

Figure 21 Contour of the air velocity vector of the whole operating room for (Case 2).

4.3 Comparison between Experimental and Numerical Results

Figures 22 to 24 show a comparison between the experimental results and the numerical results for a horizontal line generated from seven points located in the middle of the operating room at (y = 3.55 m) and at (z = 1 m) passing over the patient bed. A good agreement between the numerical and experimental results was obtained in terms of air velocity, air temperature and relative air humidity with small errors, i.e. approximately 12 %, 5% and 4% for velocity, temperature and relative humidity respectively.

These errors may have occurred due to calibration and instrument defects, which may result in differences between the CFD result and the experimental result. Also, in the experiment, the room may not have been sealed tightly enough, especially at the edges of the door some infiltration of air may have occurred. This extra heat loss was not considered in the CFD calculation, which may have resulted in differences between the CFD result and the experimental result.

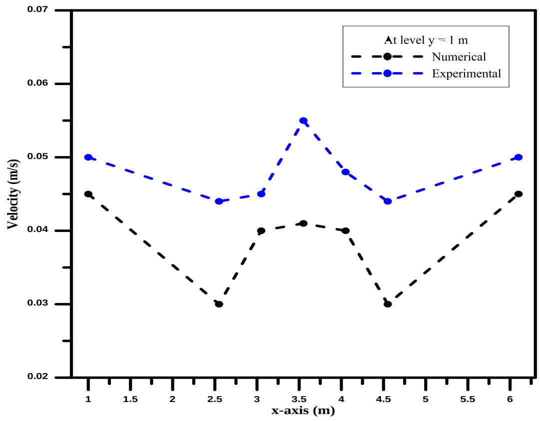

Figure 22 Comparison error for air velocity at z = 1 m and y = 3.55 m.

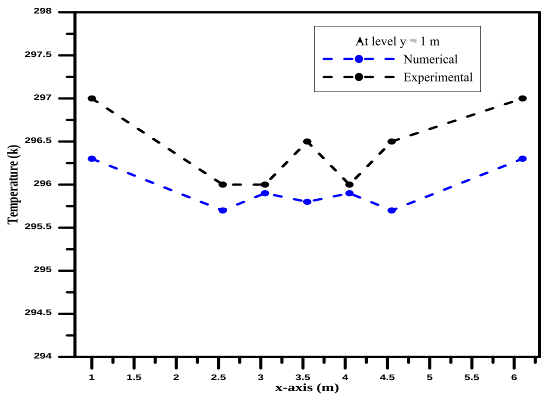

Figure 23 Comparison error for air temperature at z = 1 m and y = 3.55 m.

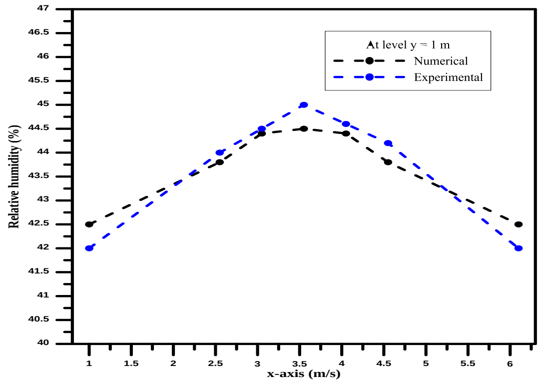

Figure 24 Comparison error for relative air humidity at z = 1 m and y = 3.55 m.

5 Conclusion

The LABVIEW software program was used to observe the experiment, obtaining a good result. There was good agreement between the numerical and the experimental results. The ceiling system provided good ventilation. The ceiling ventilation system with a plenum box located in the center is a good system that makes the air above the patient cool and well hydrated and allows the possibility of hot air movement far removed from the patient bed.

The air introduced from the ceiling through the plenum box provided great air supply at low velocity. The location of the plenum box in the center above the patient bed should be carefully chosen to provide optimum protection. The height of the room ceiling is an effective factor in air distribution. The temperature increased and the relative air humidity decreased over the field of the operating room. There was no clear impact of the small exhaust grills located at the upper corners of the operating room.

The exhaustion of 85% of the supplied air creates positive pressure inside the operating room, so the system is good for easily achieving positive pressure. For this operating room, a good range for all air parameters was obtained. The locations of both air supply and exhaust were suitable to get acceptable conditions.

References

[1] Murakami, S., Kato, S. & Suyama, Y., *Numerical Study on Diffusion Field as Affected by Arrangement of Supply and Exhaust Openings in*

Convectional Flow Type Clean Room, ASHRAE Transactions, **95**(2), pp. 113-27, 1989.

[2] Chen, Q., *Comparison of Different k–Models for Indoor Airflow Computations*, Numerical Heat Transfer, Part B; **28**, pp. 353-69, 1995.

[3] Cook, M.J. & Lomas, K.J., *Buoyancy-driven Displacement Ventilation Flows: Evaluation of Two Eddy Viscosity Turbulence Models for prediction*, Building Services Engineering Research and Technology, **19**(1), pp. 15-21, 1998.

[4] Alwan, A.A. & Hasan, A.A.F., *Experimental Study of Air Distribution within Operating Room*, The Iraqi Journal for Mechanical and Material Engineering, **14**(3), pp. 317-330, 2014.

[5] Honglu, Y.H., *Experimental and Numerical Analysis of Diffuse Ceiling Ventilation*, M.Sc. Thesis, Technical University of Denmark, pp. 51, 2011.

[6] Lstiburek, J.W., *Measurement of Ventilation and Internal Distribution*, Building and Environment Journal, **71**(Part 2), pp. 43-47, 2011.

[7] Medhat, S.M., Mohamed, T.A. & Mohamed, G.G., *Air Conditioning of a Low Ceiling Operating Theaters*, Alexandria Engineering Journal, **45**(4), pp. 387-400, 2006.

[8] Abed, E.M. & Hamza, R.A., *Experimental and Numerical Investigation of Hospital Surgery Room Air Distribution through Canopy*, The Iraqi Journal for Mechanical And Material Engineering, **17**(1), pp. 100-116, 2017.

[9] Ho, S.H., Rosario, Y.L. & Rahman, M.M., *Three Dimensional Analysis for Hospital Operating Room Thermal Comfort and Contaminant Removal*, Journal of Applied Thermal Engineering, **29**(10), pp. 2080-2092, 2009.

[10] Mohammed, M.A.,*Natural Ventilation: An Evaluation of Strategies for Improving Indoor Air Quality in Hospitals Located in Semi-arid Climates*, PhD Thesis, School of Architecture, Planning and Landscape, 2015.

[11] Alaadinn, A. & Al-shawi, A., *Prediction of Radiant Cooling Panel's Performance in Mixed Convection Environment*, M.Sc. Thesis University of Technology, Iraq, 2011.

[12] Yao, T. & Lin, Z., *Numerical Study of the Effect of Air Terminal Layouts on the Performance of Stratum Ventilation System*, 3rd International High Performance Buildings Conference at Purdue, 2014.