

## Comparison of Turbulence Models in Solving the Airflow in a Unidirectional Airflow Operating Room

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**Abstract:** Airborne infectious particles (AIP) in operating rooms are strongly related to the increased risk of surgical site infection. AIP concentration is commonly minimised using cleanroom-derived airflow systems. This study evaluates the most appropriate commercial turbulence model in simulating the airflow patterns inside a unidirectional airflow operating room. A simplified three-dimensional model representing the operating room was developed using the Computer Aided Design (CAD) software and a commercial Computational Fluid Dynamics (CFD) software was subsequently used to perform the numerical simulation. The model was discretised with an unstructured mesh that is composed of 700,000 tetrahedral elements. A no-slip condition was defined on all the surfaces of the wall. The QUICK scheme and SIMPLE algorithm were used to discretise the equations and coupled the pressure and velocity respectively. A total of four turbulence models was examined, which are: standard k-[math>\epsilon, standard k- $\omega$ , SST k- $\omega$ , and transition SST. The model validation was performed at 12 locations, which was also located at 1.2 m above floor level. The results showed that SST k- $\omega$  has the lowest average difference of about 8%, followed by the Transition SST models with a mean deviation of about 10%. Hence, both of these models are suitable for airflow studies in an operating room, while the standard k-[math>\epsilon and standard k- $\omega$  were found to overpredict the velocity magnitudes by 38% and 16% respectively.

**Keywords:** Operating room, CFD simulation, onsite measurement, turbulence models, airflow

### 1 INTRODUCTION

An operating room is the main healthcare facility used to perform surgical procedures. Most of the operating rooms worldwide utilised the cleanroom technology to provide a highly controlled and clean environment for both the patients and medical personnel [1]. To achieve a clean environment in the operating room, a common approach is utilising an efficient ventilation system to remove airborne infectious particles (AIP). It is known that personnel working in the operating room are the main source of AIP [2-4], as they can release infectious particles into the surrounding environment, even in the absence of any symptoms of skin problems [2]. Romano *et al.* [3] reported that the diameter size of infectious particles varies from 0.5  $\mu\text{m}$  to 10  $\mu\text{m}$  [3], while Wang and Chow [4] reported that the particle size could be up to 20  $\mu\text{m}$ .

Nowadays, conducting an experimental study to assess the airflow in a building is unfavourable. Such approach consumes higher financial expenses and requires a longer duration. Hence, the computational fluid dynamic (CFD) method has been extensively

used to replace experimental studies [1, 4-8]. Generally, a CFD developer provides a variety of flow models used to predict airflows ranging from low-speed indoor simulation to high-speed water jet simulation. The common commercial flow models are laminar, standard k-[math>\epsilon, realisable k-[math>\epsilon, RNG k-[math>\epsilon, standard k- $\omega$ , SST k- $\omega$ , transition SST, large eddy simulation (LES), and direct numerical simulation (DNS). So far, there is still no universal airflow model that is suitable for all type of cases. Therefore, a proper selection of the model is critical to represent the actual airflow scenario.

Recently, Wang *et al.* [9] employed the RNG k-[math>\epsilon model to predict the air and particle trajectory in enclosed environments. Tao *et al.* [10] also strongly supported that the RNG k-[math>\epsilon model is highly suitable to investigate air and particle dispersion in an indoor environment, whereas Chow and Wang [11] and Wang and Chow [4] utilised the standard k-[math>\epsilon model to simulate airflow by considering a surgeon performing bending and walking movements. They further claimed that the LES and DNS models required very demanding computer memory and calculation speed. Recent studies

conducted by Sadrizadeh *et al.* [12] and Sadrizadeh *et al.* [7] stated that the RNG k-[ $\bar{A}$ ] model is suitable to investigate low-speed airflow in an operating room.

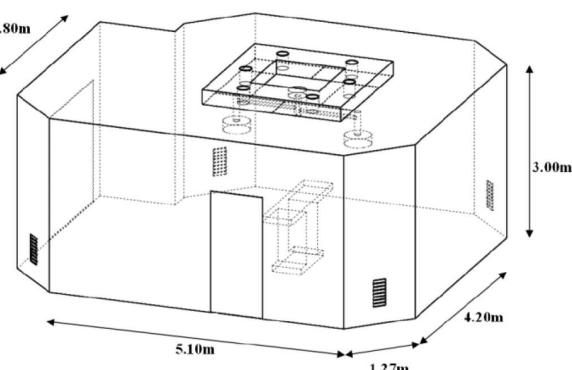
In this study, the field measurement of velocity magnitude in an actual operating room was first carried out, with all the measurement procedures in compliance with the ISO standard [13] and IEST standard [14]. Then, the CFD simulations were carried out and the results were compared with the measurement data. The objective of this paper is to evaluate the most appropriate turbulence model in predicting airflow in a unidirectional air supply operating room.

## 2 METHODOLOGY

### 2.1 Description of CFD Domain

Figure 1 shows the schematic diagram of the operating room used in this study. The room is located in one of the private hospitals in Selangor Darul Ehsan, Malaysia and categorised as an ISO Class 7 cleanroom. The dimensions of the room are as follows: 6.0 m (W)  $\times$  3.0 m (H)  $\times$  6.9 m (L).

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**Figure 1:** 3-D Diagram of Operating Room  
Air is supplied to the room via six combined air diffusers mounted on the ceiling and expelled via four exhaust grilles located at 0.25 m above the floor level. The diffusers are equipped with a High-Efficiency Particulate Air (HEPA) filter that ensures clean and unidirectional air is supplied into the room. A detailed description of the room is shown in Table 1.

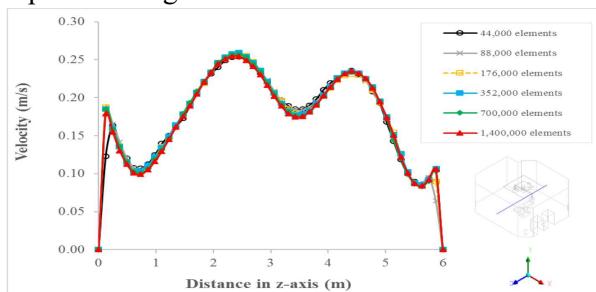
**Table 1:** Description of Operating Room

Description	
Operating System	Cleanroom System
Standard	ISO Class 7
Room Dimensions	6.0 m (W) $\times$ 3.0 m (H) $\times$ 6.9 m (L)
Exhaust Outlet	0.22 m (W) $\times$ 0.46 m (H)
Supply Air Diffuser	1.2 m (W) $\times$ 0.6 m (L)

\*\*W: width; H: height; L: length

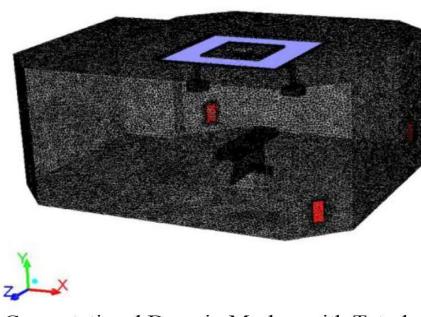
### 2.2 Meshing of Computational Domain

The ICEM software was used to mesh the computational domain of the CFD model. The model was discretised with an unstructured mesh composed of tetrahedral elements. A growth rate of 1.2 was used between the mesh layers in order to obtain a reliable prediction of the wall boundary layers. The mesh refinement was applied to the areas where a significant variation of airflow fields occurred, i.e. the surfaces of the air-supply diffusers, exhaust outlets, medical staff, surgical lamps, as well as the surgical table. To ensure the number of mesh elements was adequate, a grid independent test as depicted in Figure 2 was conducted.



**Figure 2:** Grid Independent Test for Velocity Magnitude along a Line at 1.2 m above Floor Level

Figure 2 shows the plot of velocity magnitudes along the z-axis line, with 50 equally spaced points. The coordinates of the first and last points on the line are (3.45, 1.20, 0.00) and (3.45, 1.20, 6.00) respectively. Because, both the results simulated by 700,000 elements and 1,400,000 elements were inappreciable, a total of 700,000 elements was therefore selected for subsequent simulation. The domain composed of tetrahedral cells is illustrated in Figure 3.



**Figure 3:** Computational Domain Meshes with Tetrahedral Cells

### 2.3 Solver Setup and Prescription of Boundary Conditions

All the analyses were conducted under a steady-state condition. The double-precision pressure-based solver was employed by assuming the air is incompressible, whereas the SIMPLE algorithm was

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used to couple the pressure and velocity. A comparison of the discretisation schemes was performed, as shown in Figure 4.

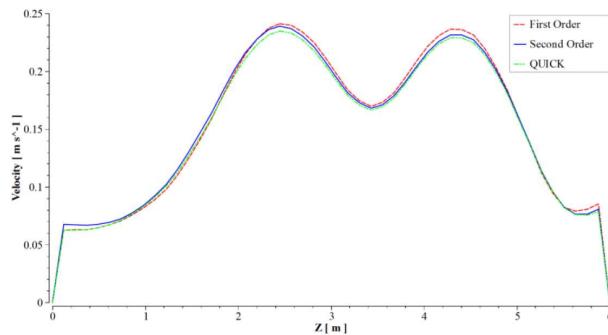


Figure 4. Comparison of Three Different Discretisation Schemes

Based on the three different schemes, the first and second orders were found to have a higher velocity magnitude at the near wall and far field regions. Therefore, the higher order scheme, known as the QUICK scheme, was utilised in this study. The reliability of the QUICK scheme has been reported in various past literatures [2, 7]. The scaled residuals were set to  $1 \times 10^{-4}$  for all equations. Negligible variations were found on the velocity magnitudes when the residuals of  $1 \times 10^{-6}$  and  $1 \times 10^{-9}$  were adopted.

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Table 2: Boundary Conditions Prescribed in CFD Model

Zone	Type	Boundary Conditions
Supply Air Diffusers	Velocity Inlet	<ul style="list-style-type: none"> <li>Velocity Specification Method: Normal to boundary</li> <li>Velocity: 0.45 m/s</li> <li>Turbulent Intensity: 5%</li> </ul>
Exhaust Outlets	Pressure Outlet	<ul style="list-style-type: none"> <li>Gauge Pressure: 0 Pa</li> </ul>
Walls/ Floor	Wall	<ul style="list-style-type: none"> <li>Wall Motion: Stationary wall</li> <li>Shear Condition: No slip</li> </ul>

Table 2 lists the boundary conditions prescribed on the CFD model for the flow analysis. The velocity of the air-supply diffusers was obtained from the field measurement, while the turbulent intensity at the diffusers for the operating room is widely reported as 5% [5, 7, 15, 16]. All airflow boundary conditions were specified in the direction normal to the respective surfaces. A zero-gauge pressure condition was set at the exhaust outlets.

#### 2.4 Comparison of Turbulence Models

A wide range of the turbulence models is available in the CFD software to simulate the airflow inside the computational domain. These are the Reynolds-Averaged Navier-Stokes (RANS) family that includes the k-[, k- $\omega$ , Transition SST, detached eddy simulation (DES), and large eddy simulation (LES) models [3, 4]. For an indoor environment simulation,

the RANS models are adequate and can produce sufficiently reliable results. However, the application of the DES and LES models demanded a very high computational power and longer computation time [2]. Therefore, in this study, the airflow was examined using the RANS models, or more specifically, the standard k-[, standard k- $\omega$ , SST k- $\omega$ , and Transition SST. Due to the limited space available in this paper, the equations for the four turbulence models are not provided, but can be found in the reference [17].

#### 2.5 Airflow Velocity Measurement

The airflow velocity measurement was conducted in August 2016. The test was carried out at a rest condition, as prescribed in the ISO standard. Typically, there are two types of testing conditions: “at rest” and “in operational” [18]. The former condition indicates that the tested room is fully furnished and preserves its original condition, but no personnel is present during the measurement [13]. For the latter case, “in operational” applies to a state where the experimental room keeps its original position while some personnel execute real working procedures [13]. This paper will not further discuss the detailed procedures of conducting the measurement as it has been elaborated by Wong *et al.* [18].

An Alnor EBT 731 manometer with an accuracy of  $\pm 4$  m/s was used to measure the airflow velocity. The measurement was executed at the sampling grid, as recommended by the IEST standard [14]. Each test grid, shown in Figure 5, should not be larger than  $30 \text{ m}^2$  [14, 18, 19].

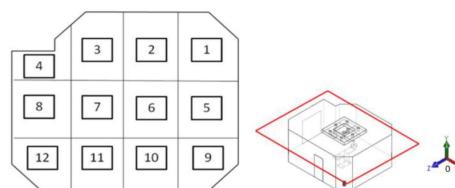


Figure 5: Sampling Locations of Airflow Velocity on a Plane 1.2 m above the Floor Level

The minimum numbers of the test grids are formulated by Equation (1):

$$N = \sqrt{A} \quad (1)$$

where  $N$  denotes the minimum number of test grids, and  $A$  denotes the area of the cleanroom in square metres. The manometer was mounted on a tripod at the height of 1.2 m above ground level. Each sampling was logged at 60-second duration to ensure a steady value is obtained.

### 3 RESULTS AND DISCUSSION

Generally, the standard k-[ model overpredicts the velocity distribution in the operating room and does not represent the actual airflow scenario. The Transition SST and SST k- $\omega$  models, however, performed well in predicting the airflow and yielded a result closest to the measured data. The mean deviation for the former and the latter were 10% and 8% respectively. The measurement data and simulated results for the velocity magnitude versus the sampling grids are plotted in Figure 6.

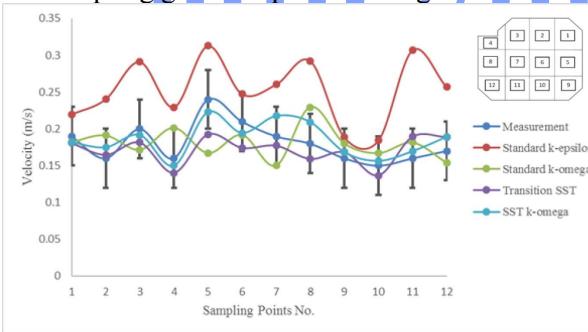


Figure 6: Comparison of Measured Data and Simulated Results

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To provide a better visualisation of the velocity distributions, a plane cutting through the middle of the room was generated, as shown in Figure 7. The plane was coloured according to the velocity magnitude and bound by four coordinates: (0.0, 0.0, 3.0), (0.0, 3.0, 3.0), (6.9, 3.0, 3.0), and (6.9, 0.0, 3.0). Among the four turbulence models, the standard k-[ model displayed a very high and concentrated airflow in the middle of the operating room, whereas the transition SST and SST k- $\omega$  turbulence models predicted lower velocity distributions, especially at the region above the operating table. This occurrence is because the transition SST and SST k- $\omega$  models are more capable of predicting the airflow with low Reynold numbers. Also, the results simulated by the SST k- $\omega$  and the transition SST were quite similar. Compared to the k- $\omega$  model, the simulated velocity magnitude was slightly higher at the height of 1.2 m above the floor level.

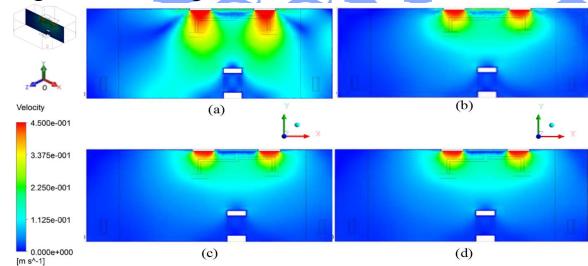


Figure 7: Velocity Contour Cut through a z-Plane at 3 m for Turbulence Model of (a) Standard k- $\epsilon$ , (b) Standard k- $\omega$ , (c) SST k- $\omega$ , and (d) Transition SST

### 4 CONCLUSION

The results obtained showed the measurement data, and the CFD results were found to be in good agreement. The SST k- $\omega$  had the lowest average difference of about 8%, followed by the transition SST and standard k- $\omega$  models with a mean deviation of about 10% and 16% respectively. The result simulated by standard k-[, however, was found to produce a significant error with a mean deviation of 38%. Among the four turbulence models, the SST k- $\omega$  produced airflow velocities closest to the measured values. Therefore, the SST k- $\omega$  model is the most appropriate turbulence model used to simulate airflow in a unidirectional airflow operating room. In terms of the simulation duration, the transition SST model consumed a much shorter time compared to the other turbulence models. Hence, the SST k- $\omega$  can be used as an alternative option when taking the calculation time and reliability of the results into consideration.

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### REFERENCES:

- [1] K. Y. Wong, H. M. Kamar, N. Kamsah, and F. M. Zawawi, "Effects of staff movement and air change rate on the airflow fields in a hospital's operating room," *International Journal of Control Theory and Applications.*, vol. 10, pp. 265-275, 2017.
- [2] S. Sadrizadeh, A. Afshari, T. Karimipanah, U. Håkansson, and P.V. Nielsen, "Numerical simulation of the impact of surgeon posture on airborne particle distribution in a turbulent mixing operating theatre," *Building and Environment*, vol. 110, pp. 140-147, 12// 2016.
- [3] F. Romano, L. Marocco, J. Gustén, and C. M. Joppolo, "Numerical and experimental

- ISSN - 2456-7841
- http://sijiret.com/
- analysis of airborne particles control in an operating theater," *Building and Environment*, vol. 89, pp. 369-379, 2015.
- [4] J. Wang and T.-T. Chow, "Influence of human movement on the transport of airborne infectious particles in hospital," *Journal of Building Performance Simulation*, vol. 8, pp. 205-215, 2015.
- [5] S. Sadrizadeh and S. Holmberg, "Effect of a portable ultra-clean exponential airflow unit on the particle distribution in an operating room," *Particuology*, vol. 18, pp. 170-178, 2015.
- [6] S. Sadrizadeh, A. Tammelin, P. Ekolind, and S. Holmberg, "Influence of staff number and internal constellation on surgical site infection in an operating room," *Particuology*, vol. 13, pp. 42-51, 2014.
- [7] S. Sadrizadeh, S. Holmberg, and P. V. Nielsen, "Three distinct surgical clothing systems in a turbulent mixing operating room equipped with mobile ultraclean laminar airflow screen: A numerical evaluation," *Science and Technology for the Built Environment*, vol. 22, pp. 337-345, 2016/04/02 2016.
- [8] J. Wang and T.-T. Chow, "Numerical investigation of influence of human walking on dispersion and deposition of expiratory droplets in airborne infection isolation room," *Building and Environment*, vol. 46, pp. 1993-2002, 10// 2011.
- [9] M. Wang, C.-H. Lin, and Q. Chen, "Advanced turbulence models for predicting particle transport in enclosed environments," *Building and Environment*, vol. 47, pp. 40-49, 1// 2012.
- [10] Y. Tao, K. Inthavong, and J. Tu, "Computational fluid dynamics study of human-induced wake and particle dispersion in indoor environment," *Indoor and Built Environment*, p. 1420326X16661025, 2016.
- [11] T.-T. Chow and J. Wang, "Dynamic simulation on impact of surgeon bending movement on bacteria-carrying particles distribution in operating theatre," *Building and Environment*, vol. 57, pp. 68-80, 2012.
- [12] S. Sadrizadeh, S. Holmberg, and A. Tammelin, "A numerical investigation of vertical and horizontal laminar airflow ventilation in an operating room," *Building and Environment*, vol. 82, pp. 517-525, 2014.
- [13] I. S. O. Standard, "ISO 14644-1, Cleanrooms and associated controlled environments," in *Classification of air cleanliness*, ed. United Kingdom: Institute of Environmental Sciences and Technology, 1999.
- [14] I. E. S. T. Standard, "IEST-RP-CC006.2," in *Testing Cleanrooms*, ed: Institute of Environmental Sciences and Technology, 1997.
- [15] C. Balocco, G. Petrone, and G. Cammarata, "Numerical Investigation of Different Airflow Schemes in a Real Operating Theatre," *Journal of Biomedical Science and Engineering*, vol. Vol.08No.02, p. 17, 2015.
- [16] Y. Yau and L. Ding, "A case study on the air distribution in an operating room at Sarawak General Hospital Heart Centre (SGHHC) in Malaysia," *Indoor and Built Environment*, vol. 23, pp. 1129-1141, 2014.
- [17] A. Fluent, "Ansys fluent theory guide," *ANSYS Inc., USA*, vol. 15317, pp. 724-746, 2011.
- [18] K. Y. Wong, H. M. Kamar, N. Kamsah, M. S. Deris, and H. Tan, "Comparison of cleanroom performance in hospital culture and vascular interventional radiology laboratories," *International Journal of Advances in Science Engineering and Technology*, vol. 4, pp. 71-75, 2016.
- [19] K. Y. Wong, H. M. Kamar, N. Kamsah, F. M. Zawawi, M. N. Musa, and M. S. Deris, "A systematic assessment of cleanroom performance in hospital's operating room," *Proceedings of 9th & 10th IAARHIES International Conferences*, pp. 6-11, 2016.
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