Thermal comfort of the surgical staff in an operating theatre: a numerical study on laminar and mixing ventilation systems

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SUMMARY

The indoor air quality in an operating theatre affects both patient health and the well-being of the surgical team members. Health care facilities, and operating theatres in particular, require ventilation and air conditioning for thermal comfort and removal of contaminants. Although the patient undergoing surgery is given the highest priority, it is important to consider the comfort of surgical staff, as it has a direct influence on their work quality and thus on the patient.

This paper presents a numerical analysis for thermal comfort in a hospital operating theater, as based on the Predicted Mean Vote index. The room model includes a patient and five surgical staff members. Two types of ventilation systems, that is, mixing and laminar airflow were considered. Computational fluid dynamics was used to predict airflow, heat transfer, and thermal comfort. The predicted mean vote and dissatisfaction percentage were calculated for surgical staff thermal comfort. Results indicated that mixing ventilation might slightly improve thermal comfort, by reducing the temperature difference between the head and ankle levels.

Keywords: thermal comfort, PMV-PPD index, Computational Fluid Dynamics, Hospital operating theatre, fully mixed ventilation system, laminar airflow

1. INTRODUCTION

In hospital environment, the prediction of thermal comfort perception of patients and health care personnel is essential for architectural and building systems design, as well as for establishing clothing guidelines. The ventilation system of a hospital operating theatre (OT) is necessary to provide a healthy and comfortable environment for the surgical team member and the patient. Staff thermal comfort can be deduced from the metabolic rate, clothing insulation, and environmental conditions, that is, temperature, humidity, and airflow. Thermal comfort as a parameter of indoor air quality in a hospital has a critical impact on working conditions, well-being, safety and health of medical staffs. Inappropriate thermal comfort conditions in an OT may reduce the work efficiency and increase the possibility of the surgical errors. Thermal comfort evaluation within an enclosed environment is usually determined through the use of Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) indices (ISO 7730:2005, 2005). PPD predicts the number of thermally dissatisfied persons among a large group of people. There are many studies about the examination of thermal comfort in hospital environment (Ho, Rosario, & Rahman, 2009; Hwang, Lin, Cheng, & Chien, 2007; Van Gaever, Jacobs, Diltoer, Peeters, & Vanlanduit, 2014; Verheyen, Theys, Allonsius, & Descamps, 2011). Ho et al. (Ho et al., 2009) reported that airflow pattern and relative humidity have a significant impact on staff thermal sensation.
Gaever et al. (Van Gaever et al., 2014) concluded that the current HVAC (heating, ventilating, and air conditioning) standards and systems cannot provide a comfortable thermal environment for all surgical staff members; however, Verheyen et al. (Verheyen et al., 2011) found that the thermal environment in Belgian healthcare facilities is acceptable for 95% of the patients. It is almost impossible to provide all occupants with 100% acceptable indoor thermal conditions as different persons may have a different perception of prevailing indoor conditions. The difference in thermal perception normally depends on various factors, including different activity levels, metabolic rate, clothing insulation, and even working positions. Preferable thermal comfort conditions were reported for anaesthesiologists 23–24 °C, for nurses 22–24.5 °C, and for surgeons 18–19 °C. For patients, however, the recommended air temperature falls in the range of 24–26 °C (Balaras, Dascalaki, & Gaglia, 2007).

The current study examines the thermal comfort of staff members in a hospital operating theatre. CFD modelling is used to find the numerical solution for the airflow, heat, and mass transfer inside the OT. Thermal comfort evaluation is introduced briefly through applying the PMV index model and relevant PPD parameters.

2. METHODOLOGIES

CASE STUDY

To evaluate the thermal comfort in an OT, several parameters need to be predicted, including air velocity, temperature, humidity, and turbulence intensity. These can be done by solving the system of coupled equations for the conservation of mass, momentum, and energy. Figure 1-a shows the internal OT configurations and figures 1-b and 1-c show the examined ventilation system, that is, mixing and LAF.

The OT measures 8.5 m × 7.7 m, with a floor-to-ceiling height of 3.2 m. The OT contains an operating table, two instrument tables, two medical lamps (with thermal load of 320 W/m²), two pieces of medical equipment (with thermal load of 255 W/m²) and 10 surgical staff (with thermal load of 116 W/m²). The discrete ordinates (DO) radiation model was used to determine the heat flux contribution. Two ventilation principles, turbulent-mixing airflow and laminar airflow, were implemented with the identical internal configuration of staff and furnishings (see Figs. 1-b,c). The inlet air supplied the OT with identical conditions for both ventilation principles and had a total flow rate of 2 m³/s, temperature of 20 °C, and inlet relative humidity of 40%.
3. NUMERICAL MODELLING

The airflow was simulated using the RNG k–ε turbulence model. Model validation work was already given by the authors (Sadrizadeh & Holmberg, 2014b; Sadrizadeh, Tammelin, Ekolind, & Holmberg, 2014) and thus not repeated here. Humidity was handled by species transport calculations for water vapor in OT air. The Fluent V16.0 CFD code was used to solve the governing equations of fluid flow. Grid independence tests were performed using three different densities.

PMV is a parameter for thermal comfort evaluation in an enclosed environment based on the temperature and humidity conditions along with air velocity, metabolic rate, and clothing system. In the current study, a user-defined function calculated the relative humidity and, further, the PMV from the CFD simulation results. The PMV and PPD values can be calculated as follows:

\[
PMV = [0.303 \exp(-0.036M) + 0.028] \\
\times \left[ (M - W) - 3.69 \times 10^{-8} f_{cl} [(T_{cl} + 273.15)^4 - (T_r + 273.15)^4] \\
- f_{cl} h_{conv}(T_{cl} - T_a) - 3.05[5.733 - 0.007(M - W) - 0.001p_w] \\
- 0.42[(M - W) - 58.15] - 0.0173M(5.867 - 0.001p_w) \\
- 0.0014M(34 - T_a) \right]
\]

\[
PPD = 100 - 0.95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)
\]

A more detailed explanation of the above equation is given in ISO 7730-2005 (ISO 7730:2005, 2005). A seven-point thermal sensation scale of PMV was summarized in Table 1. The acceptable thermal environment for general comfort is recommended to be in the range of \((-0.5 < PMV < 0.5)\).

<table>
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<th>Table 1: Seven-point thermal sensation scale</th>
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<tr>
<td>+3</td>
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Figure 2 shows the PPD index as a function of PMV. It is clearly shown that optimum thermal conditions are within the range of \(-0.5 < PMV < 0.5\).
4. RESULTS AND DISCUSSION

AIRFLOW FIELD

Figure 3 shows the airflow at the center plane of the operating table, which indicates different patterns within the surgical zone. The velocity distributions for the LAF systems show the strong and unidirectional downflow patterns in the critical surgical zone; however, strong recirculation can be observed in the case of the turbulent mixing system.

When the OT was supplied by the LAF system, a strong reverse airflow pattern (eddy) was observed in its outer edges. However, the air streams passing across the surgical area came directly from the supply diffuser, ensuring effective washing. The strong downward airflow may cause thermal discomfort for the surgical staff, which will be accessed in the next section of this study. In the case of turbulent-mixing ventilation, reverse flows occurred in most parts of the OT. In addition, airflow stagnation occurred in the OT corners that represent the worst case in terms of air age.

5. RELATIVE HUMIDITY AND THERMAL COMFORT

Figure 4 shows the contour plot of relative humidity in steady state situation for both mixing and LAF ventilation system in the OT center.

The exported required value from the CFD simulation (i.e., air temperature and velocity, humidity, and radiative temperature) and different combinations of metabolic rate and clothing insulation make it possible to calculate PMV and PPD indices.

Figure 5 shows those indices for two examined ventilation systems. Comparing the PMV and PPD results for both mixing and LAF systems indicated that slightly more
thermally satisfactory results could be achieved when the OT is supplied by the mixing ventilation.

![Fig. 5: PMV and PPD for the mixing and LAF ventilation systems](image)

The highest dissatisfaction can be observed mostly in the head and neck area of surgical team members, resulting in PMV value of about two. This implies that surgical staff may feel slightly warm; thus, PPD value is predicted in the range of 70–80%. Further investigation is needed to consider additional parameters such as a local draft rate in order to more precisely assess the thermal comfort situation in the OT.

6. CONCLUSION

This study presents a CFD analysis of air velocity, relative humidity, and thermal comfort in an operating theatre. The PMV and PPD were calculated under two ventilation principles (i.e., turbulent mixing and LAF) to evaluate thermal comfort of the surgical staff. It was found that slightly more thermal satisfaction might be achieved by mixing OT principles. However, mixing ventilation systems may not equal LAF in terms of contaminant removal efficiency (Sadrizadeh & Holmberg, 2014a).

In experimental studies, thermal comfort assessment is usually done by considering the mean air velocity and temperature, as well as mean relative humidity over the entire OT space. Nevertheless, the mean of above-mentioned quantities may vary spatially when the OT uses an LAF ventilation system.

7. REFERENCES


