Numerical Assessment of the Influence of Heat Loads on the Performance of Temperature-Controlled Airflow in an Operating Room

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ABSTRACT

Airborne bacteria-carrying particles (BCPs) in an operating room (OR) can cause post-operative infections in the patients. The ventilation system in the OR is crucial in removing or diluting airborne BCPs. This study numerically assessed a newly developed OR ventilation scheme – temperature-controlled airflow (TAF), with special focus on the influence of heat loads on the airflow and BCPs concentration. TAF supplies clean air at different temperature levels to different zones and establishes a high-momentum downward airflow pattern over the operating table. The results show that TAF is an efficient ventilation system that can provide good protection for the patients under low to moderately heavy heat loads. When the heat load is further increased to an extremely heavy level, the desired airflow pattern cannot be achieved and TAF becomes less efficient. The numerical results also suggest that the supply air temperature needs to be optimized according to the specific use conditions to maximize the performance of TAF.

KEYWORDS

temperature-controlled airflow, bacteria-carrying particles, ventilation system, operating room, heat load.

1 INTRODUCTION

A low level of airborne bacteria-carrying particles (BCPs) in the operating room (OR) is one of the key factors to prevent post-operative infections. In a large multicenter study of 8000 total hip and knee replacement, Lidwell (Lidwell, 1983) found a linear correlation between airborne BCPs concentration and the rate of deep infections. The major source of BCPs in an OR is human skin scales shed from the surgical staff (Hoffman et al., 2002). A person releases about 10 million particles per day during moderate physical activity; approximately 5–10% of these particles carry bacteria (Hambraeus, 1988). Due to the growing resistance to antibiotics, operating room ventilation has become increasingly important in minimizing airborne contamination and thus reducing the risk of infections. An ill-functioning OR ventilation system not only increases the risk of infections and brings unnecessary sufferings to the patients, but also imposes heavy financial burdens on healthcare services.

Modern operating rooms are commonly ventilated by a laminar airflow (LAF) system. The filtered and particle-free air is delivered from a ceiling diffuser right above the operating table at a high flow rate. While not truly laminar, the supply air moves at a nearly uniform velocity and creates a unidirectional airflow pattern. LAF normally uses a large airflow rate, so that the downward incoming air can have sufficient momentum and directly wash BCPs away from the patient. Previous studies have shown that the performance of LAF can be easily affected by the obstructions in the airflow path such as the surgical lamps (Chow and Yang, 2003; Wang et al., 2018) and the posture of the surgical staff (Chow and Wang, 2012; Sadrizadeh et al., 2016).

A new ventilation principle, temperature-controlled airflow (TAF), has recently been implemented and evaluated (Alsved et al., 2018). In contrast to LAF that utilizes isothermal air, TAF supplies clean air at two different temperature levels. The slightly cooler air is discharged into the surgical zone through ceiling-mounted central diffusers, whereas slightly warmer air is dispersed into the periphery of the OR through additional surrounding diffusers. The supply air temperature is adjusted and controlled to establish a temperature gradient of 1.5 – 3 ℃ between the central supply air and the ambient air. The central supply air is accelerated by gravity due to the buoyancy effect and falls down to the operating table with high momentum. Similar to LAF, the downward airflow in TAF is also expected to wash away BCPs in the surgical critical zone. The surrounding supply air suppresses the air recirculation in the periphery of the OR and further dilutes the airborne BCPs contamination in the air.

The authors' previous studies have shown that TAF can serve as an energy-efficient alternative to LAF and also has the advantage over LAF in overcoming obstructions in the airflow path (Wang et al., 2018). Specifically, the airflow pattern in TAF is less sensitive to the physical disturbances created by the surgical lamp than that in LAF. These studies confirm that TAF utilizing the buoyancy effect uses the airflow more efficiently and robustly than LAF that relies on high momentum. However, the upward convective current developed from heat sources (i.e. the surgical staff and equipment) interacts with the downward incoming air and may deteriorate the performance of TAF. Heavy heat loads may develop strong upward thermal plumes, which prevent the incoming air from being delivered to the surgical site. In this study, we applied Computational Fluid Dynamics (CFD) to investigate the influence of heat loads on the airflow pattern and airborne BCPs dispersion in a TAF ventilated OR.

2 METHODS

The physical configuration of the OR was shown in Figure 1. The OR had a dimension of 8.5 m × 7.7 m × 3.2 m (Length × Width × Height). Cooler air at 18.5 ℃ was supplied to the surgical zone through eight central diffusers annularly distributed on the ceiling. Warmer air at 20 ℃ was introduced into the periphery of the OR from 18 additional ceiling-mounted surrounding diffusers. The total airflow rate was 2.5 m^3/s and was evenly distributed between each individual diffuser. Room air was extracted by five low-level exhaust vents located on the sidewalls.

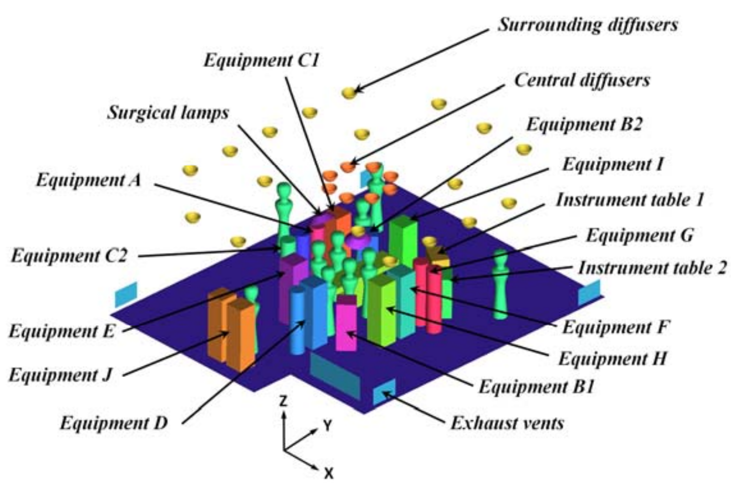

Figure 1: An overview of the OR configuration.

An operating table was placed in the center of the OR. Two instrument tables were located next to each other downstream the surgical zone. Ten surgical staff members were present in the OR and each person emitted a heat of 81 W. Two surgical lamps were fixed above the heads of the staff, which created a total heat load of 215 W. The OR general lighting contributes to a heat load of 2412 W, emitted from the ceiling. Twelve pieces of equipment were included in the OR, representing the most commonly used medical equipment during surgical procedures. Table 1 lists the rated power of each piece of equipment.

Table 1: Rated Power of the Medical Equipment Used in the Operating Room

Equipment	Power [W]	Equipment	Power [W]
A	200	E	453
B1	250	F	152
B2	400	G	400
C1	495	H	101
C2	159	I	238
D	496	J	401

To investigate the influence of heat loads on the performance of TAF, four simulation cases were performed with heat loads gradually increased by 25% of the rated power of the equipment from Case 1 to Case 4. Specifically, Case 1 uses only 25% of the rated power of the equipment, whereas in Case 4 the heat emitted from the equipment was considered 100% of the rated power. Table 2 lists the heat loads of each simulation case.

Table 2: Heat Loads in Case 1, Case 2, Case 3 and Casr 4.

	Case 1	Case 2	Case 3	Case 4
Equipment [W]	936	1873	2809	3745
Surgical lamps [W]	215	215	215	215
General lighting [W]	2412	2412	2412	2412
Surgical staff [W]	810	810	810	810
Total [W]	4373	5310	6246	7182

The amount of BCPs disseminated from each person, measured as Colony Forming Unit (CFU), varies widely with individuals, clothing, and activity level. In this study, we assumed that the staff wore ordinary scrub suites and source strength of 5 CFU/s was adopted for each staff member. The diameter of the BCPs was taken as 12 µm, the average size of skin scales released from a person (Noble, 1975).

The airflow field and BCPs dispersion were numerically solved by the commercial CFD code – ANSYS Fluent 18.2. The turbulent flow was modeled by the realizable k-epsilon model. The particle motion was computed by the Lagrangian particle tracking (LPT) approach. All surfaces in the computational domain were considered as adiabatic, except the ceiling and the exposed surfaces of persons and equipment. The no-slip condition was used for velocity at all rigid surfaces and the pressure-outlet condition was specified at all exhaust vents. The BCPs concentration was sampled at 20 cm above the center of the operating table and instrument tables. Numerical model details and validation can be found in the authors' previous studies (Sadrizadeh et al., 2014; Wang et al., 2018)).

3 RESULTS AND DISCUSSIONS

Figure 2 and 3 present the temperature contour at two vertical planes passing the center of the operating table for the four simulation cases.

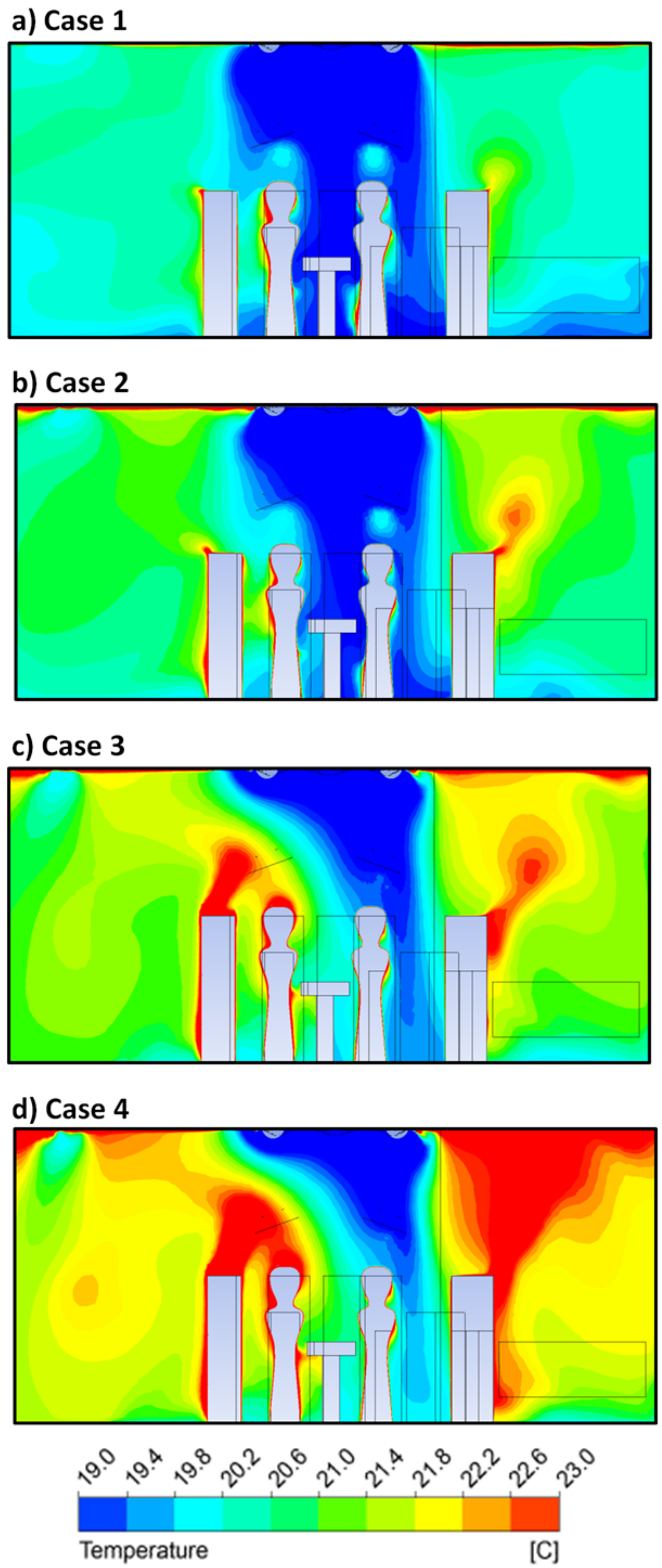

Figure 2: Temperature contour plot at the XZ plane passing the centre of the operating table for the four cases.

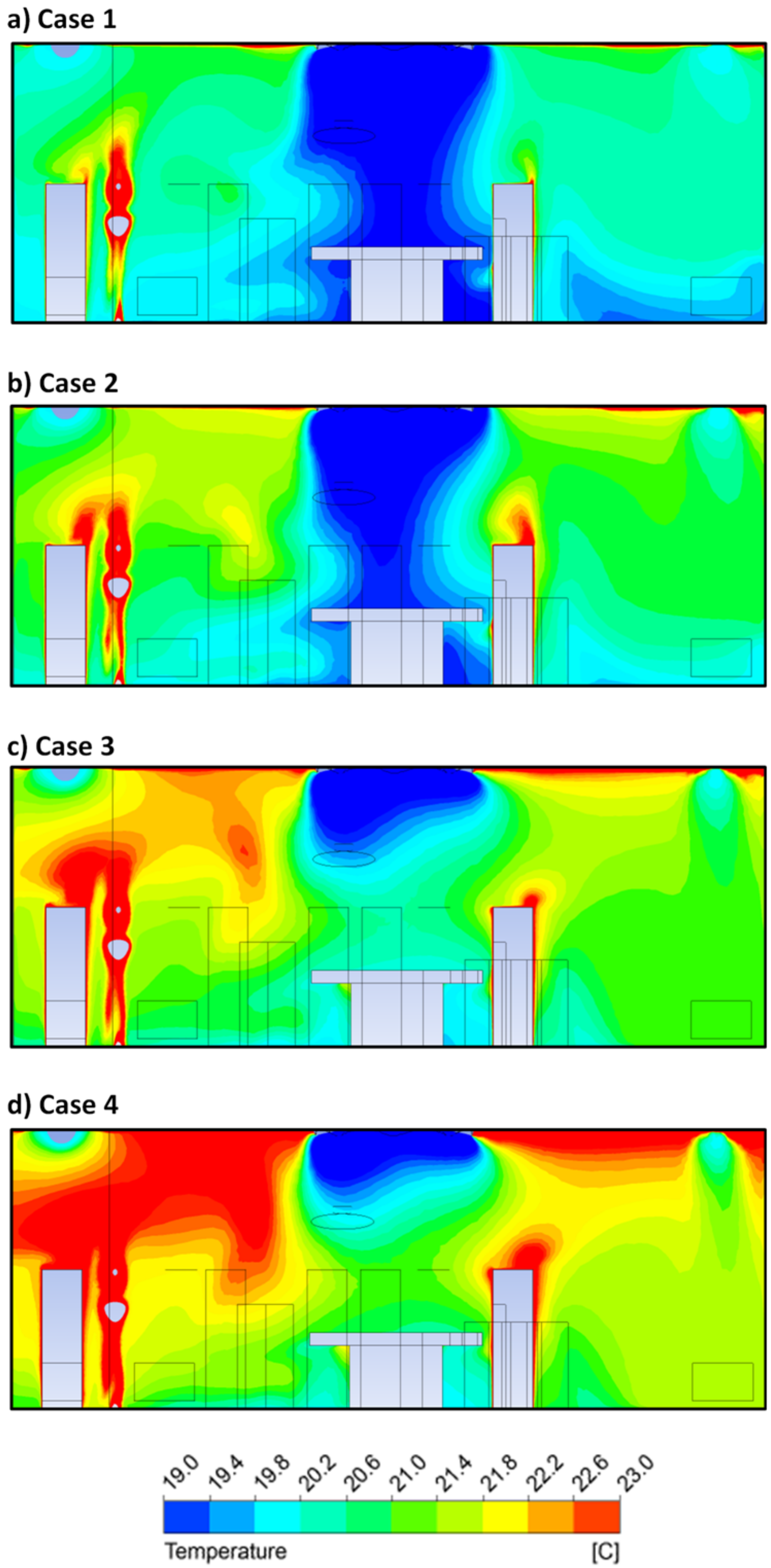

Figure 3: Temperature contour plot at the YZ plane passing the centre of the operating table for the four cases.

In Case 1 and 2, the central supply air directly falls down to the operating table and establishes a downward airflow field over the operating table. Thus, the airflow is expected to wash away BCPs from the operating zone. However, a significant change in the airflow pattern is observed in Case 3 and 4, where the thermal plumes developed from the equipment and staff push away the downward airflow and thus the incoming clean air could not directly reach the operating table. Consequently, as the surgical staff serves as the source of both heat and contamination, the upward convective current may entrain a significant amount of BCPs into the surgical area.

Figure 4 presents the simulated airborne BCPs concentration at the operating table and two instrument tables. At the operating table, Case 3 and 4 result in significantly higher BCPs concentration than Case 1 and Case 2. Specifically, an abrupt increase in BCPs concentration is observed when increasing the heat load from Case 2 to Case 3. This indicates changes in the airflow pattern, as confirmed by the temperature contour plot in Figure 2 and 3. The washing effect is severely weakened and the dilution effect plays a more important role in Case 3 and 4. Therefore, furthering increasing the heat load from Case 3 to Case 4 only slightly increases the BCPs concentration at the operating table. Interestingly, from Case 1 to Case 2, the BCPs concentration decreases as the heat load increases. This can be ascribed to the fact that a heavier heat load results in a higher ambient temperature and therefore a higher temperature gradient, which strengthens the driving force acting on the incoming supply air. As a consequence, the downward airflow in Case 2 provides a stronger washing effect and thus better air cleanliness than in Case 1.

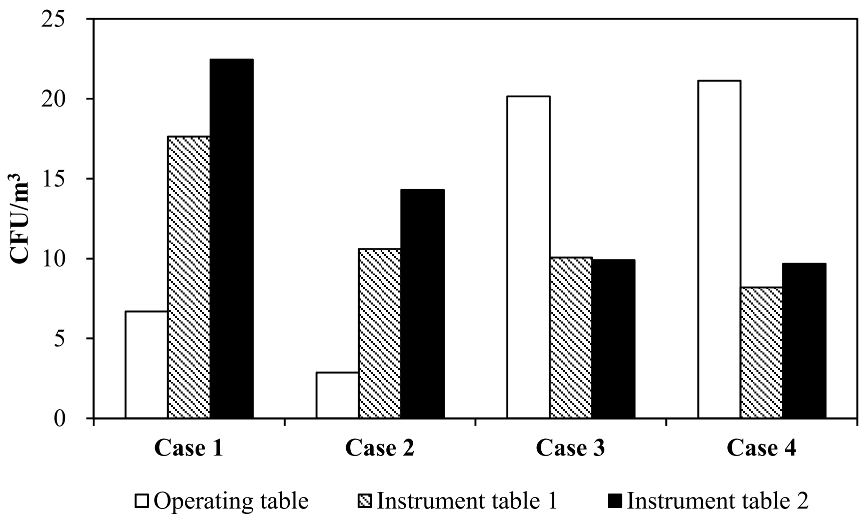

Figure 4: Simulated airborne BCPs concentration at the operating table and instrument tables.

The two instrument tables were placed next to the heating emitting equipment outside the protection zone of the central diffusers. The dilution principle replaced the washing effect, that is, the airflow diluted the airborne contamination rather directly washed away infectious particles. The BCPs concentration at the instrument tables shows a slightly declining trend as the heat loads increases. This is due to the fact that higher heat dissipation leads to stronger upward thermal plumes generated from the equipment, which have more chance to lift particles out of the range of the instrument tables.

The results suggest that the TAF system can function properly under moderately high heat loads and provide good protection for the patients. However, when the heat load becomes extremely heavy, it is difficult for TAF to establish the desired airflow pattern and TAF fails to provide the efficient washing effect. Despite the distorted airflow pattern, TAF is still able to work as mixing ventilation and dilute the airborne contamination. The simulated level of BCPs concentration in different cases also implies that the supply air temperature needs to be optimized according to specific use conditions to maximize the performance of TAF.

4 CONCLUSIONS

In this study, we numerically investigated the performance of a new ventilation system – temperature controlled airflow (TAF), with respect to BCPs concentration under four different heat load conditions. The realizable k-epsilon model was applied to treat the turbulent flow and the Lagrangian particle tracking approach was used to model the particle motion. The TAF system supplies the airflow at different temperature levels in different zones. By taking advantage of the buoyancy effect, TAF is capable of creating a unidirectional downward airflow pattern in the surgical zone and providing adequate washing effect above the operating table. The results show that TAF can tolerate moderately heavy heat loads and provide good protection for the patients. A slightly higher heat load can even help improve the performance of TAF. Under the condition of extremely heavy heat loads, TAF cannot achieve the desired airflow pattern in the critical zone and the performance can be degraded. Even with a distorted airflow field, however, TAF can still function as mixing ventilation and dilutes the airborne contamination. This study, along with previous studies, confirms that TAF represents an efficient and reliable ventilation strategy for operating rooms.

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