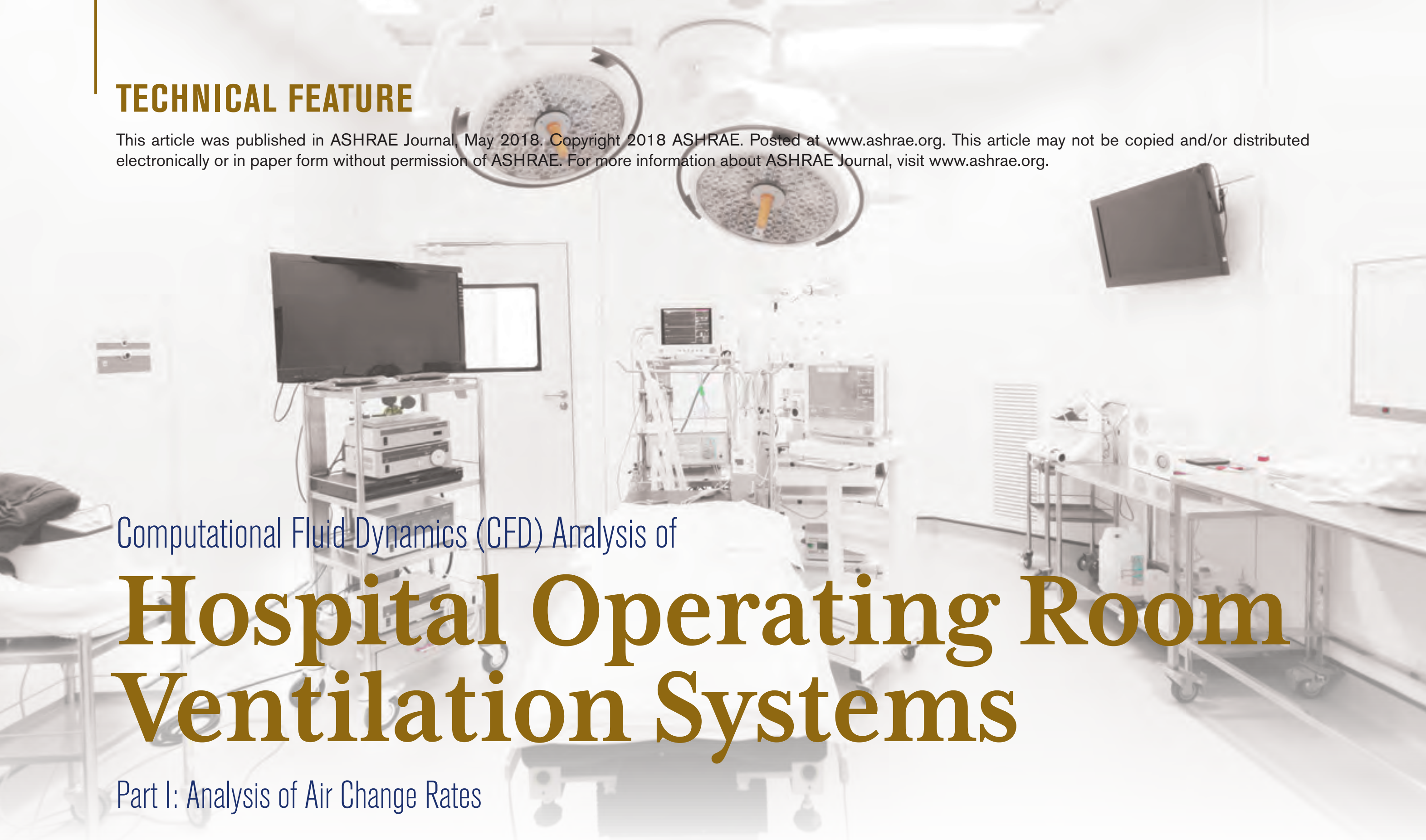

TECHNICAL FEATURE

Computational Fluid Dynamics (CFD) Analysis of

Hospital Operating Room Ventilation Systems

Part I: Analysis of Air Change Rates

BY KISHOR KHANKARI, PH.D., FELLOW ASHRAE

The primary objective of hospital operating room (OR) ventilation systems is to minimize surgical site infection due to airborne contaminants and bacteria and to provide a comfortable environment for surgeons and other staff in the room. The key factor in reducing surgical site infection is to minimize the contamination of the sterile (clean) zone where the surgical procedures are performed. One source of infection in the OR is squames, which are skin scales shed from the exposed skin of occupants in the room.[1] Once airborne, these bacteria-carrying particulates generally follow the path of airflow in the room. The OR ventilation system should effectively sweep these particulates out of the sterile zone and minimize their re-entrainment from non-sterile (contaminated) zones.

ASHRAE/ASHE Standard 170-2017[2] provides minimum requirements for the design and layout of the ventilation systems in operating rooms which presumably can maintain a sterile environment around the surgical site. According to this standard, diffuser array should provide airflow over the patient and surgical team. Furthermore, the coverage area of the primary supply diffuser array should extend a minimum of 12 in. (305 mm) beyond the footprint of the surgical table on each side. The room should be equipped with at least two low sidewall exhaust grilles placed at opposite corners, with the bottom of these exhaust grilles installed approximately 8 in. (203 mm) above the floor. In addition, the OR should maintain positive pressure with a total of 20 air changes per hour (ACH) supplied with 4 ACH outside air. The supply air should be unidirectional directed downward with an average discharge velocity of 25 to 35 fpm (0.13 to 0.18 m/s). These specifications for minimum discharge velocities are based on previous CFD studies, which concluded that such velocities and the coverage area of the diffuser array would overcome the rising buoyant plumes from the sensible heat sources (i.e., surgical lights in the sterile zone), as well as protect the surgical site by allowing a local thermal plume to develop from a relatively "warm" surgical site.[3] The later assumption, however, could not be verified by the ASHRAE-funded research project on

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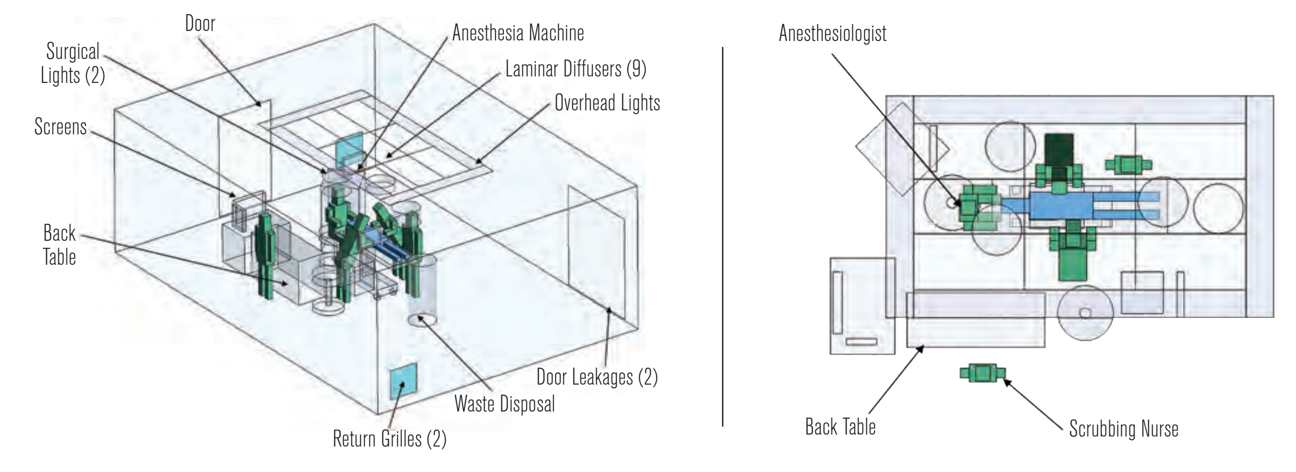
FIGURE 1 Diagram of CFD model of a hospital operating room. (Left) Isometric View. (Right) Plan View.



experimental evaluation of hospital OR ventilation systems.[4] It should be noted that the role ASHRAE standards is to provide only "minimum requirements," which may not be the optimal design guidelines.

Air is the primary carrier of heat, moisture, contaminants, and airborne particulates in operating rooms. The distribution of supply air and the associated flow path of the air determine the resulting air velocities, temperature, and concentration of contaminants, and flow path of airborne particulates at various locations in the room. Such distribution, in turn, determines thermal comfort, air quality, and potential for transmission of airborne particulates. Ideally, in an operating room the supply air should pass through the sterile zone and exit through exhaust grilles in a "single pass" manner without recirculation and mixing with the supply airstream. It is generally believed that high air change rates can yield a cleaner environment in the operating rooms. However, recent studies indicate increasing ACH does not necessarily provide a cleaner environment but substantially increases the operating costs.[5]

The airflow patterns, temperature distribution, and resulting flow path of airborne contaminants can depend on several interrelated factors including the location, type, and number of supply diffusers; supply air change rates and supply air temperature; locations and strengths of various heat sources in a room, including the ambient and surgical lights; size and location of equipment in the room that can obstruct the flow path of the air and contaminants; size and locations of room returns; and perhaps also on the frequency of opening and closing OR doors. Physical testing and real time measurements of all the parameters that can affect the performance of the OR

FIGURE 2 Airflow patterns at central plane in the operating room for three different ACH showing similar airflow patterns; with air recirculation and entrainment at the edge of the sterile zone.

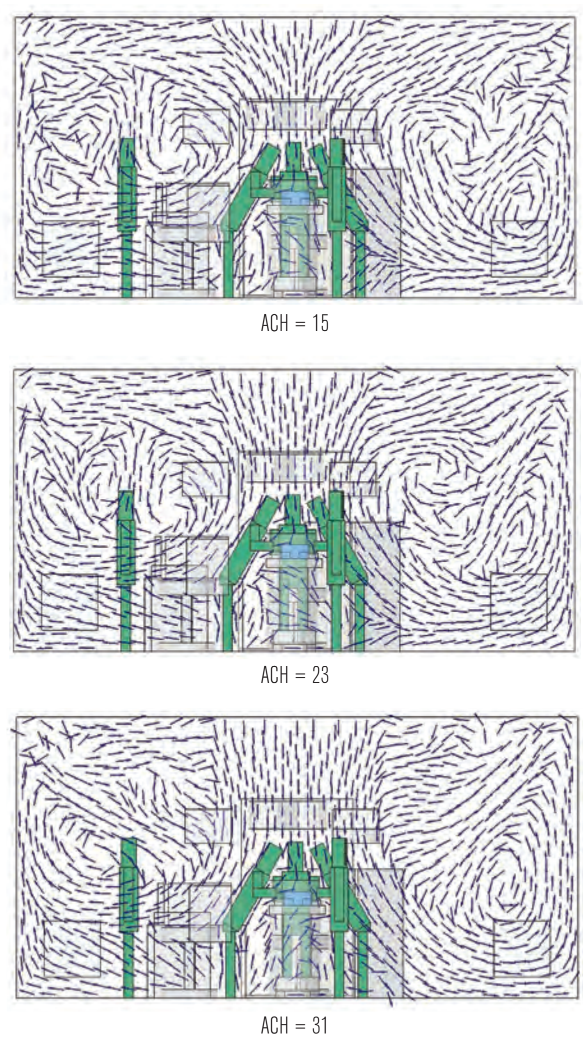


FIGURE 3 Contours of air velocity at central plane in the operating room for three different ACH rates showing the discharge air accelerates as it approaches the operating table, with higher velocity zones (shown in red) occurring near the edge of the sterile zone at higher ACH.

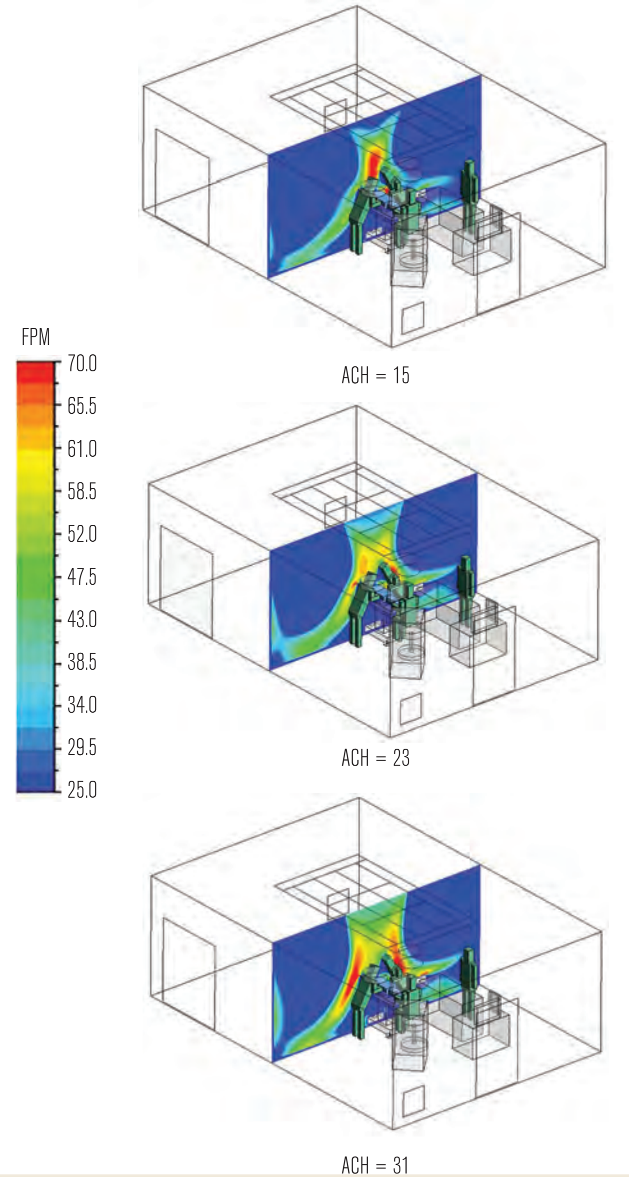
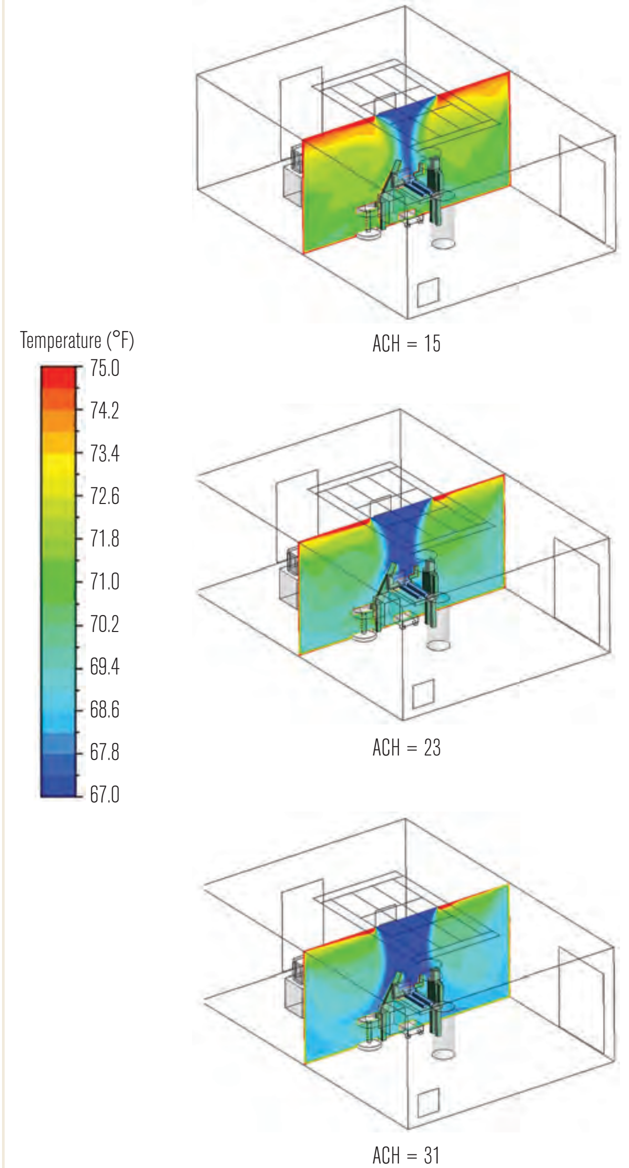


FIGURE 4 Contours of air temperature at central plane in the operating room showing thermal stratification occurs at all three different ACH, and increasing ACH minimizes the contraction of the supply air jet and decreases the average temperature in the OR.



ventilation system including the airflow patterns and the resulting flow path of contaminants is not feasible, if not impossible.[1,4,5,6] In such situations CFD analyses may provide a feasible alternative based on sound scientific laws of physics, including laws of air motion and heat transfer. CFD analyses provide detailed three-dimensional visualization of airflow and temperature distributions ultimately leading to valuable insights of airflow patterns and the resulting flow path of airborne contaminants.

The main objective of this CFD study is to evaluate the impact ACH on the airflow patterns, temperature distribution, and on the probable flow path of airborne particulates in a typical OR. This study also attempts to analyze the impact of supply airflow rates on the entrainment of the surrounding air into the sterile zone by evaluating the acceleration of centerline velocity of the supply air jet. A follow-up CFD study, which will be published in a future issue will analyze the impact of HVAC configuration on the performance of OR ventilation systems.

Virtual Setup of the Operating Room

A three-dimensional, steady-state, non-isothermal

FIGURE 5 Flow path of airborne particulates originating from the occupants inside the sterile zone demonstrating particles being swept from the sterile zone into the non-sterile zone where they recirculate before exiting the OR, at three different ACH.

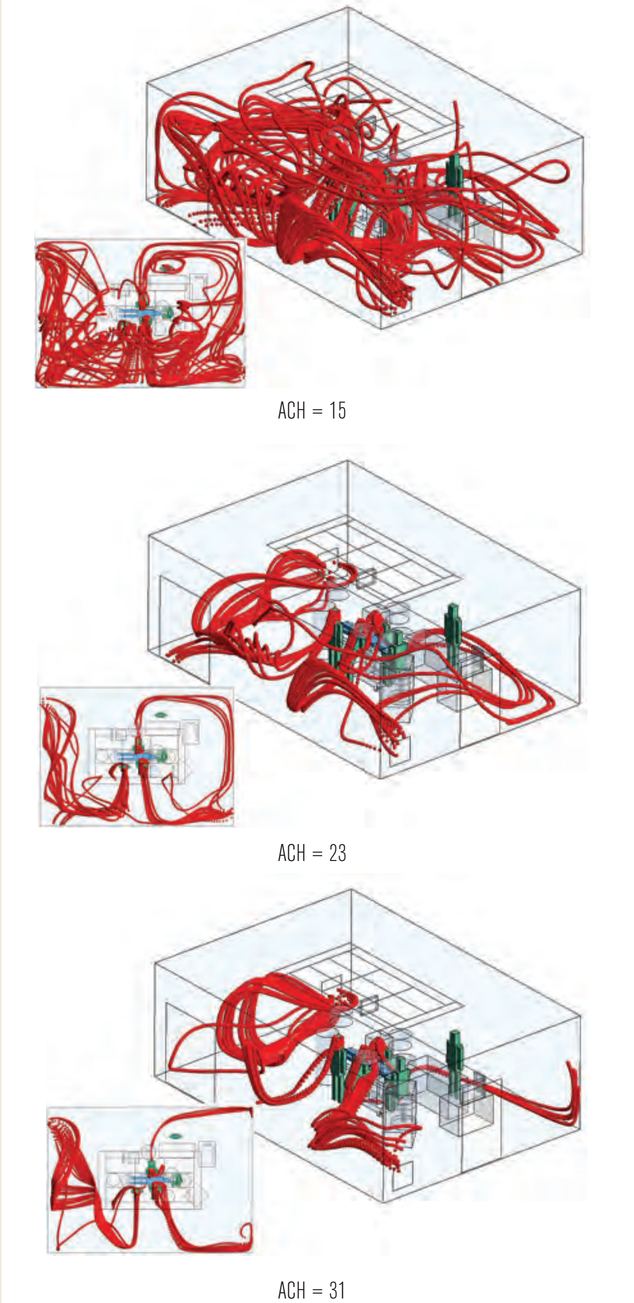
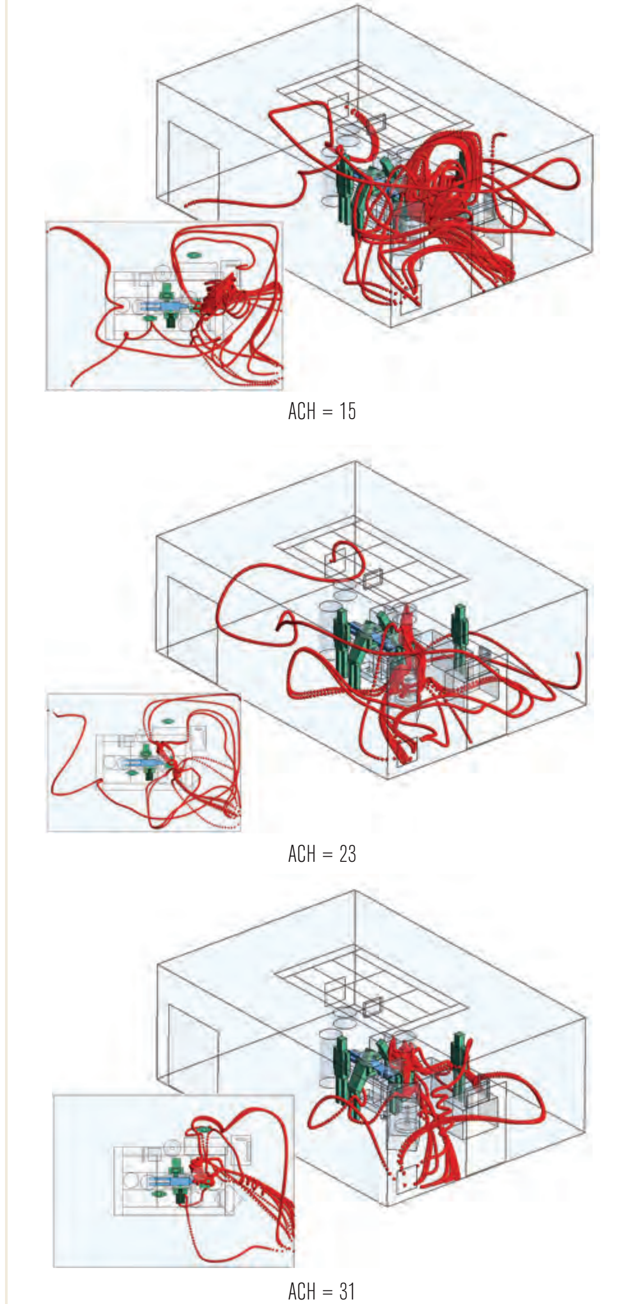


FIGURE 6 Flow path of airborne particulates originating from the anesthesiologist at the edge of the sterile zone demonstrating particles being swept from the sterile zone into the non-sterile zone before exiting the OR, at three different ACH.

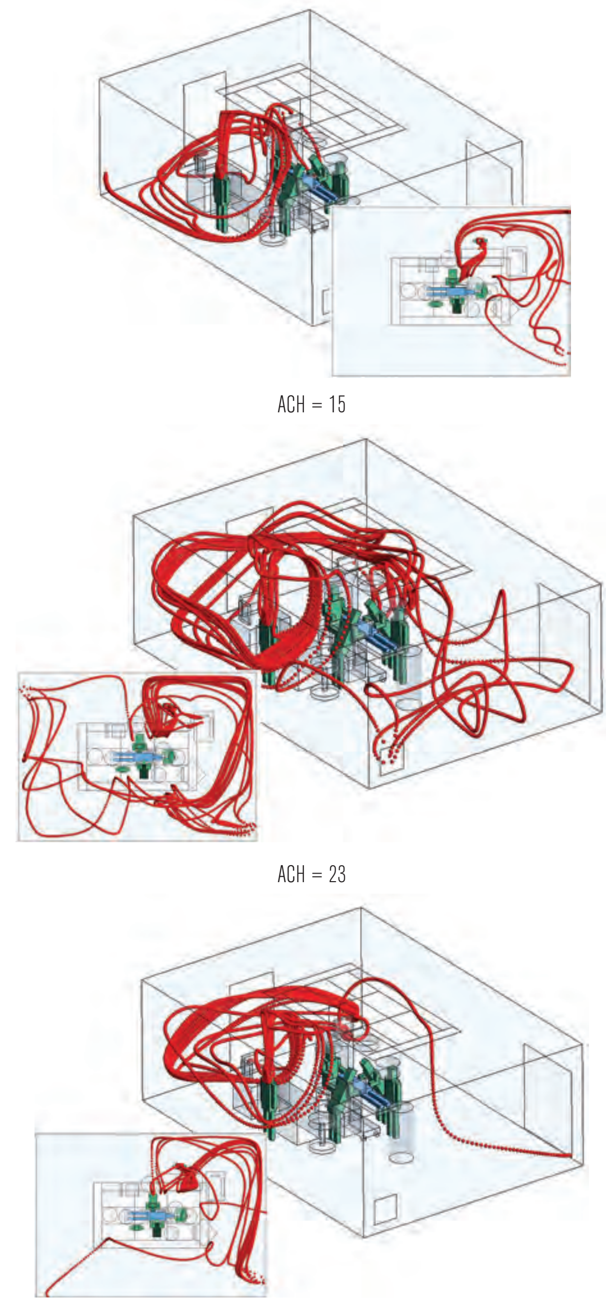


CFD model of a hospital OR is developed for this study as per the minimum requirements stated in Standard 170-2017.[2] The room has about 560 ft^2 (52 m^2) floor area (28 × 20 ft [8.5 × 6 m]) with 10 ft (3 m) ceiling height. As shown in *Figure 1* (page 15), the virtual OR has an operating table with a patient, two surgeons, two nurses, anesthesiologist, surgical lights, overhead lights, and several other pieces of equipment and furniture. These are sources of sensible heat and also obstructions to the airflow. Most of these entities are located within the sterile zone (under the array of laminar "unidirectional" diffusers) except the scrubbing nurse and the back table. The air is supplied through a single array of nine laminar flow diffusers (72 ft^2 [6.7 m^2]) located at the center of the room ceiling. The room air is exhausted through two exhaust grilles located on opposite walls and through the leakage openings located under the two doors. The effect of supply airflow rate is analyzed by varying the diffuser discharge air velocity from 20, 30, and 40 fpm (0.1, 0.15, and 0.2 m/s), which correspond to 15, 23, and 31 ACH, respectively. The exhaust flow rate through the exhaust grilles was maintained lower than the supply flow rate such that the exhaust flow rate (leakage) through the two door openings remains at 350 cfm (165 L/s), and thus, the room was maintained at positive pressure.

The sensible heat loads due to the occupants and the overhead lights were assumed to be 1500 Btu/h (440 W) and 2457 Btu/h (720 W), respectively. The total sensible heat load due to the other equipment, including the anesthesia machine, screens, surgical lights, and monitors was assumed to be 3583 Btu/h (1050 W). Thus, the total sensible heat load in the room was assumed to be 7,540 Btu/h (2210 W). The supply air temperature was set at 67°F (19.4°C) which maintained the average room temperature at 70°F (21°C). The supply airflow rate at 30 fpm (0.15 m/s) is in accordance with the minimum requirements in ASHRAE Standard 170-2017.[2] This study did not analyze the transport of moisture and resulting relative humidity in the space.

The standard k-epsilon (k-ε) turbulence model was employed to compute the turbulent viscosity of the air. The probable flow paths of airborne particulates are analyzed by tracking the airflow path streamlines released from the occupant's faces which are probably the most exposed skin surfaces of the surgeons. The particulates are assumed to be skin squames which are about 10 microns in diameter.[3] This analysis assumes most of the airborne particles released from the occupant's faces would follow the flow path of the air. Particles less than 20 microns can readily follow the flow path of the air.[4] Since the main goal of the proposed analysis is to analyze the flow path of airborne particles, any settling and deposition of these particulates on the surfaces is not explicitly considered in this study.

FIGURE 7 Flow path of airborne particulates originating from the scrubbing nurse located outside the sterile zone showing entrainment of the particles back into the sterile zone for all three ACH.



ACH = 15

ACH = 23

ACH = 31

Results and Discussion

Airflow Patterns

The analyses for three different supply airflow rates show similar airflow patterns (*Figure 2,* page 15). In all three cases, the air from the non-sterile zone entrains at the edges of the sterile zone. While the air near the floor moves away from the sterile zone towards the exhaust grilles, the air in the middle and upper sections of the room moves from the non-sterile zone into the sterile zone. Also, in all three cases the discharge air from the laminar diffusers accelerates as it approaches the operating table (*Figure 3,* page 16). However, the location of this high velocity zone changes with the supply airflow rates.

In the case of low airflow rate (15 ACH) the zone of high velocity is formed almost at the center of the sterile zone. In the case of higher airflow rates (23 and 31 ACH) the zone of high velocity moves towards the outer region of the sterile zone. Furthermore, in the case of 31 ACH, the zones of high velocity form on either the side of the operating table. These analyses indicate the entrainment of the surrounding air into the sterile zone occurs independent of supply airflow rates, as it occurs at all three levels of the supply airflow rates. These patterns are consistent with the experimental observations from an ASHRAE Research Project.[4]

Temperature Distribution

These analyses show temperature stratification occurs at all levels of the supply airflow rates (*Figure 4*, page 16). Hot air accumulates near the ceiling surrounding the array of laminar diffusers, while cooler air remains near the floor. It is important to note that the temperature difference between the supply air jet and surrounding air near the ceiling can be much larger than the theoretical average temperature difference between supply air temperatures and return air (average room temperature) temperature. This can adversely affect the airflow pattern causing entrainment of the air near the ceiling. In the case of 15 ACH flow rate, the supply air maintains its initial temperature of 67°F (19.4°C) only in the central core of the sterile zone and shows significant contraction of the supply air jet. Such phenomenon is also reported during the experimental evaluation of airflow patterns in a mock operating room.[4] Due to entrainment of the surrounding hot air into the sterile zone, with the exception of the core region, the temperature at the other locations remains higher than the supply air temperature. With increasing airflow rate, as in the cases of 23 and 31 ACH, the region of the sterile zone occupied by the cold supply air increases and the extent of the contraction of the supply jet core reduces. Similarly, with increasing airflow rates, as expected, the temperature gradient between the sterile and non-sterile zone reduces.

Flow Path of Airborne Particulates

The probable flow paths of the airborne particulates are analyzed for three different release locations: (1) from the face of the surgeons and nurse located inside the sterile zone; (2) from the face of the anesthesiologist located at the edge of the sterile zone; and (3) from the face of the scrubbing nurse located outside of the sterile zone. When the airborne particulates are released within the sterile zone they are readily swept out of the sterile zone without any significant entrainment (*Figure 5*, page 18). This pattern is consistent for all three cases of the ACH. These particulates can circulate and mix with the air in the non-sterile zone before exiting the OR, however, at low ACH these particles may accumulate in the non-sterile zone.

When the airborne particulates are released from the anesthesiologist located at the outer edge of the sterile zone, they are also swept away from the sterile zone (*Figure 6*, page 18). These particulates also tend to circulate within the non-sterile zone before exiting the room. In the case of the low airflow rate of 15 and 23 ACH, these particulates may get entrained into the outer edges of the sterile zone, whereas in the case of the high airflow rate of 31 ACH they readily exit the OR without significant recirculation in the non-sterile zone.

In the final scenario, where airborne particulates are released from the face of a scrubbing nurse located outside the sterile zone, the particulates initially move upward toward the ceiling, and then get entrained back into the sterile zone. This occurs at all three ACH rates. After passing through the sterile zone, they follow the similar path of those particulates that originate from within the sterile zone (*Figure 7*, page 19). After exiting the sterile zone, the particulates can circulate and mix with the air in the non-sterile zone before exiting the OR.

It should be noted in all these cases the particles are swept away from the critical zone surrounding the patient. However, the particulates tend to remain and circulate in the non-sterile zone before exiting the OR, which increases the probability of their entrainment into the sterile zone. Since the two exhaust grilles are located in the two opposite corners of the room, the particulates take a convoluted path to eventually exit the room. During this time prior to exiting the room, these particles have the opportunity to deposit on the back table located in the non-sterile zone. This is consistent with the results of previous studies.[1,3,4,6] The size, location, and number of the exhaust grilles play an important role in determining the flow path of airborne contaminants, especially in the non-sterile zone. Previous studies of airflow paths in the patient room indicated that modifications in the air supply and return locations can significantly alter the flow path of airborne contaminants.[8]

Analysis of Centerline Velocity

Hospital operating rooms are often characterized by high sensible heat loads concentrated within a relatively small sterile zone. Heat released from various equipment and surgical lights can cause hot air to rise locally against the incoming cold supply air. Additionally, as described before, a zone of high temperature and thermal stratification often forms surrounding the cold supply air jets. The temperature gradients between the sterile and non-sterile zone can cause acceleration of the supply air jet from the laminar diffusers, which in turn, may promote undesirable entrainment of the surrounding contaminated air from the non-sterile zone into the clean sterile zone.

Due to the recirculation pattern of the entrained air in and out of the sterile zone, it is difficult to quantify the exact flow rate of the recirculated air between the sterile and non-sterile zone. The extent of acceleration in the centerline velocity of the supply air along the vertical centerline from the ceiling to the floor can provide an indirect estimate of this entrainment. Archimedes Number (Ar), a non-dimensional parameter, is a ratio of the buoyancy force and the inertial force of the downward air jet. The supply airflow rates of 15, 23, and 31 ACH (discharge velocity of 20, 30, and 40 fpm [0.1, 0.15, and 0.2 m/s]) correspond to the Ar number of 21, 6.3, and 2.7, respectively. Details regarding the calculation of Ar are given in an ASHRAE Research report.[4] Increasing the discharge velocity (increasing the mass flow rate of the supply air) reduces theoretical temperature difference between supply and return temperature (ΔT), which in turn, results in lowering the Ar. Therefore, at higher airflow rates the lower values of Ar indicate flow dominated by inertial force.

Figure 8 shows the variation of non-dimensional velocity (a ratio of centerline velocity at a specific distance along the vertical centerline to the discharge velocity at the exit of the laminar diffuser). This variation is plotted against the non-dimensional vertical distance—a ratio of the height at a specific vertical location to height of the laminar diffuser from the ceiling. Thus at a non-dimensional height of 0.0 at the laminar diffuser, the non-dimensional centerline velocity is 1.0. This analysis indicates for all three levels of the supply airflow rates the centerline velocity increases as the air jet moves downward towards the operating table. However, with increasing supply airflow rate the relative acceleration of the centerline velocity reduces. It shows in the case of low 15 ACH (Ar 21) the centerline velocity reaches about 3.4 times of the initial discharge velocity at about 38% of the vertical distance from the ceiling. Whereas in the case of 23 ACH (Ar 6.3) and 31 ACH (Ar 2.7) it reaches about 1.8 and 1.3 times of the respective discharge velocities. This indicates that reducing the temperature gradient between the sterile and non-sterile zone can reduce the acceleration of the supply air jet. This is consistent with the experimental measurements of the velocity profiles.[4,7] It should be noted that irrespective of the supply airflow rate, the peak in the non-dimensional velocity occurs between 36% to 38% of the vertical distance from the laminar flow diffuser.

However, such acceleration of centerline velocity does not provide any insights into the flow path of the particulates. Therefore, reducing the discharge velocity or Archimedes Number alone may not help in minimizing the entrainment of airborne particulates from non-sterile zone to sterile zone. Similar investigations for the operating room HVAC configuration may help to clarify whether such modifications in HVAC configuration, especially in the non-sterile zone, will reduce the entrainment of airborne particulates from non-sterile zone into the sterile zone. This will be presented in the second part of this study.

Summary and Conclusions

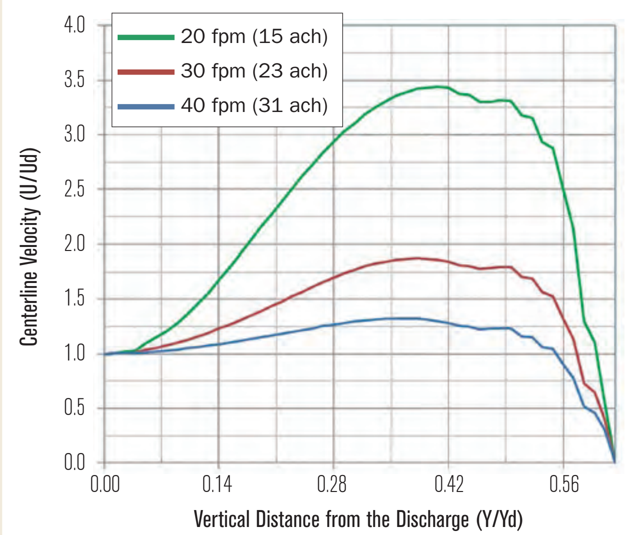
CFD analyses of a hospital operating room are performed to analyze the impact of supply airflow rates or ACH on the airflow patterns, temperature distribution, and resulting flow path of airborne particulates. Additionally, the impact of supply airflow rates on the acceleration of centerline velocity of the supply air jet was also evaluated.

These analyses indicate the supply airflow rate, and hence, the discharge velocity of the unidirectional air jet, has a little impact on the overall airflow patterns, resulting thermal stratification, and on the flow path of airborne contaminants in the hospital OR. When the particulates are originated within a sterile zone or at the edge of the sterile zone they are generally swept away into the non-sterile zone where they can recirculate within the non-sterile zone without significant re-entrainment. However, when such particulates originate in the non-sterile zone, for example from the face of a scrubbing nurse, irrespective of the supply airflow rate, they get entrained into the sterile zone. For all the cases of supply airflow rates, and irrespective of the origin of the release, the particulates tend to stay and circulate in the non-sterile zone before exiting the OR which potentially can increase the probability of deposition of these particles on the back table which is generally located in the non-sterile zone.

Increasing the supply airflow rates and the associated heat capacity of the supply air helps in reducing the thermal gradients between the sterile and non-sterile zone which in turn reduces the contraction of the supply air jet, indicating the potential reduction in the entrainment of air from the non-sterile zone into the sterile zone. This study also indicates the velocity of the discharge air jet increases at it travels towards the operating table. However, such acceleration in the discharge velocity reduces with increasing the supply airflow rate.

High ACH can potentially reduce the overall temperature levels in the OR; reduce the thermal gradients across the sterile and non-sterile zones; reduce the acceleration of the discharge air jet; and potentially

FIGURE 8 Variation of non-dimensional centerline velocity along the normalized distance from the laminar diffuser shows that the discharge velocity increases as it approached the operating table. Such increase in the velocity reduces with increasing ACH.



minimize recirculation of airborne particulates in the non-sterile zone. However, high ACH add to the initial and operating costs of OR ventilation systems and it cannot alter the overall airflow patterns and the resulting flow path of the airborne contaminants (including possible entrainment of airborne particulates from the non-sterile zone into the sterile zone).

HVAC configuration including the size, number, and locations of supply and return of the air may play a role in determining the flow path of airborne contaminants, especially in the non-sterile zone. By altering the airflow patterns in the non-sterile zone, the flow of path of these particulates may be altered to avoid entrainment. The legacy HVAC design for hospital operating rooms involving a ceiling array of laminar supply diffusers and low wall exhaust grilles on the opposite walls needs further evaluation to minimize the transfer of airborne particulates from non-sterile to sterile zones.

Acknowledgments

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