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Inspirations From Cleanroom HVAC Technologies

Reducing Airborne Contamination, Transmission & Migration

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HVAC technologies used in cleanrooms can achieve ultralow airborne contamination, transmission and migration to meet industrial specifications. Traditionally, people assume cleanrooms consume high levels of energy, and their technologies and associated costs are only justified for high-tech sectors. However, emerging design concepts and approaches are becoming more cost-effective and energy efficient while achieving excellent airborne cleanliness performance. Many mitigation strategies have been studied to tackle COVID-19 challenges in airborne contamination control. Cleanrooms' unique and mature air handling, distribution, cascading, segregation and filtration techniques may encourage experimenting with some of its concepts for commercial spaces to achieve better airborne infectious disease transmission control where applicable and cost-effective.

Cleanroom and HVAC Design Complexity

A cleanroom is an enclosed space in which airborne particles (both nonviable and viable) are controlled and classified. A cleanroom is designed, constructed and operated to minimize particle generation and retention inside the room, as well as migration from adjacent spaces to accomplish ultrahigh-purity airborne and surface-borne cleanliness.

In addition to controlling cleanroom temperature, humidity and ventilation rate,its airflow pattern, pressure, filtration, particle and gaseous concentrations, etc., also need to be well controlled and quantitatively tested to meet stringent ISO 14644 standards and process specifications. If a cleanroom's supply airflow rate varies, the room's airflow pattern, pressure differential, contaminant removal and particle/microbial/gaseous concentrations are going to be altered or distorted

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almost instantaneously. To maintain all these room conditions within specified tolerances, cleanroom HVAC system design is often much more complex and complicated than that for commercial spaces.

Indoor Air Cleanliness

Table 1 shows the ISO 14644-1 standard's maximum air particulate concentration limits, which correlate the ISO classes with particle sizes and allowable concentration in each size. As examples, ISO Class 5 is often required for pharmaceutical filling chambers where syringes and vaccine vials are filled, sealed and used for human-injectable products. ISO Class 3 to Class 5 is often specified for environments where wafers and computer chips are made. ISO Class 1 and Class 2 environments are frequently designed for nanotechnology or ultrafine particulate processing.

A typical office or residential room, if unoccupied and undisturbed for a few hours, sometimes can achieve ISO Class 9 or Class 8. However, once the room is occupied it will quickly fall out of the cleanroom classifications. Therefore, air cleanliness in commercial spaces is not far distant from those of low-end cleanrooms; the key difference is the latter uses a set of specialized control concepts and techniques to drastically enhance air cleanliness in not only as-built but operational conditions.

TABLE 1 Air cleanliness by particle concentration.[1]

ISO CLASS NUMBER	MAXIMUM ALLOWABLE PARTICLE CONCENTRATION (COUNTS/m^3) EQUAL TO AND GREATER THAN THE CONSIDERED SIZES[1]					
	0.1 µm	0.2 µm	0.3 µm	0.5 µm	1.0 µm	5.0 µm
Class 1	10					
Class 2	100	24	10			
Class 3	1,000	237	102	35		
Class 4	10,000	2,370	1,020	352	83	
Class 5	100,000	23,700	10,200	3,520	832	
Class 6	1,000,000	237,000	102,000	35,200	8,320	293
Class 7				352,000	83,200	2,930
Class 8				3,520,000	832,000	29,300
Class 9				35,200,000	8,320,000	293,000

Particle Sources and Airborne Contamination Controls

Particles can be generated or emitted internally within a room from people, process, equipment and room enclosure materials. Fine particles can be brought in externally through outdoor ventilation air even adequately filtered in an air-handling unit (AHU). Particles can further migrate into a room from adjacent rooms through door operations and through cracks in the room enclosure. *Table 2* shows various measures to control contamination, including efforts for commercial spaces.

Cleanroom Flow Patterns & Air Change Rates

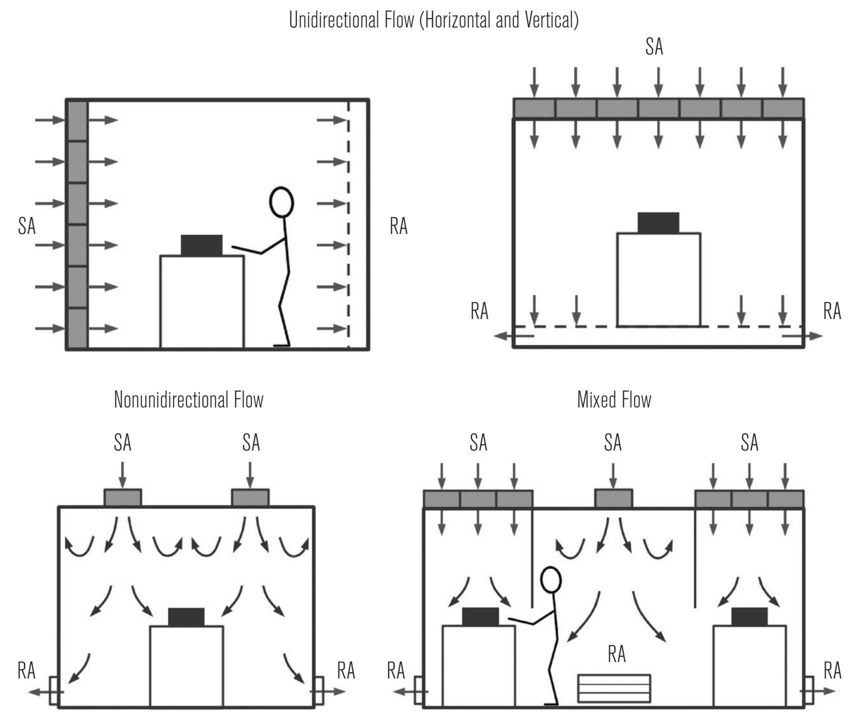
A cleaner zone is often surrounded by peripheral zones of lower cleanliness. Movement of material and personnel between adjacent zones through doors and

TABLE 2 Indoor airborne particle (viable and nonviable) controls for cleanrooms and commercial spaces. (Courtesy of Wei Sun, P.E., from his ASHRAE Distinguished Lecturer Presentation)

	SOURCE CONTROL	DILUTION WITH FILTRATION	TRANSMISSION CONTROL	MIGRATION CONTROL
CLEANROOMS	Control source-strength by reduction, isolation and/or removal. Isolate particle generations with containment devices and remove particles directly from room by using: ▪ Lower emission rate ▪ Mask and gowning ▪ Fume hood ▪ Snorkel local exhaust ▪ Equipment integral exhaust ▪ Purge/flush cycle ▪ UVGI or hydrogen peroxide (H_2O_2) disinfection	If contaminants are still released into room volume, then room concentration can be reduced through the dilution of HEPA (≥99.97% efficiency) or ULPA (≥99.997% efficiency) filtered supply air to minimize particles' entry through dilution air, typically the higher of air change rate, the lower of room contaminant concentration. ach may range from 15 to 600, mainly through secondary recirculation air instead of primary AHU air.	Keep distance from contaminant sources. Use segregation and cascading airflow arrangement.	Apply pressurization or depressurization. Install anteroom or airlock.
COMMERCIAL SPACES	Control source-strength is not common, but optional methods can be applied with: ▪ Mask ▪ Return air to be the main path for contaminant exit, no local exhaust. ▪ Flush cycle to be integrated into AHU.	Multiple layers of filters in AHU, combined efficiency 60% to 85%, efficiency could be increased to reduce contaminant reentry through supply air. ach may range from 3 to 12, all through primary AHU air, secondary recirculation air is not common.	Supply air uses "shared return airs" from multiple rooms within same AHU zone; fine particles emitted from other rooms could reenter room, even filtered in AHU. Distance from potential source if required.	Not typical.

pass-throughs increases the risk of contaminants' migration. Either the dilution or displacement airflow concept can be used based on cleanliness class. In *Figure 1*, "unidirectional flow" pattern (typically with ceiling supply and raised floor return) uses higher air velocity (70 fpm to 90 fpm [0.36 m/s to 0.46 m/s]) and air change rate (ach) (250 ach to 600 ach), mainly by the air displacement concept for ISO Class 1 through Class 5 cleanrooms; "nonunidirectional flow" pattern (typically with ceiling supply and low sidewall return) uses lower air change rate (15 ach to 120 ach), mainly by the air dilution concept for Class 7, Class 8 and Class 9 cleanrooms; either pattern can be used for mid-range cleanrooms (Class 6 and Class 7, 120 ach to 250 ach); and "mixed flow" has both patterns within one room.

FIGURE 1 Cleanroom airflow patterns.[1]



The terminology of air change per hour (ach) has been confusing to many since it was introduced. It is simply a flow rate (expressed for supply air [SA], return air [RA] or exhaust air [EA]) normalized by the room volume as an "airflow intensity measure" in a relative term; the "hour" is a convenient time unit, while flow rate (in cfm or L/s) is an absolute term. Once a room's dimension is fixed, its ach and SA values are in a proportional relationship and mutually convertible; they are the two sides of the same coin. The ach can be used for flow intensity comparison, while flow rate is used directly for design settings. Airflow intensity can be alternatively expressed in a room flow rate normalized by its floor area.

Transmission Controls by Airflow Cascade (Protection for Personnel, Room and Product)

Unlike for commercial spaces where personnel's comfort/health is the focus of the HVAC system, cleanroom HVAC systems can provide protection not only for personnel, but also for room environment and process/product by using proper cascading in up-mid-down airstream arrangements as demonstrated in *Figure 2*.

External Contaminant Migration Controls

When all doors are closed, particles can migrate mainly through unintentional cracks (such as air gaps around doorframes or duct/pipe wall penetrations) into a room. Pressurization can be used to minimize particle migration between rooms through properly controlled supply, return and exhaust airflow rates to each room within the controlled suite.[4]

However, when a door is being opened, the prior pressure differential across the room enclosure disappears simultaneously and particles can migrate through the doorway. An effective containment is to install an anteroom or airlock to tackle the transient challenge.[5] References 4 and 5 provide detailed strategies for both door-closed (static) and door-in-operation (transient) conditions, respectively.

AHU Configurations

Shown in *Figure 3*, ISO Class 9 and 8 cleanrooms commonly use a single primary AHU loop that provides heating, cooling, ventilation, plus filtration and dilution to achieve room air cleanliness. Their HVAC systems are similar to those used for commercial spaces.

ISO Class 7, Class 6 and Class 5 cleanrooms require

FIGURE 2 Cleanroom HVAC design could protect not only personnel, but also room and product.[1]

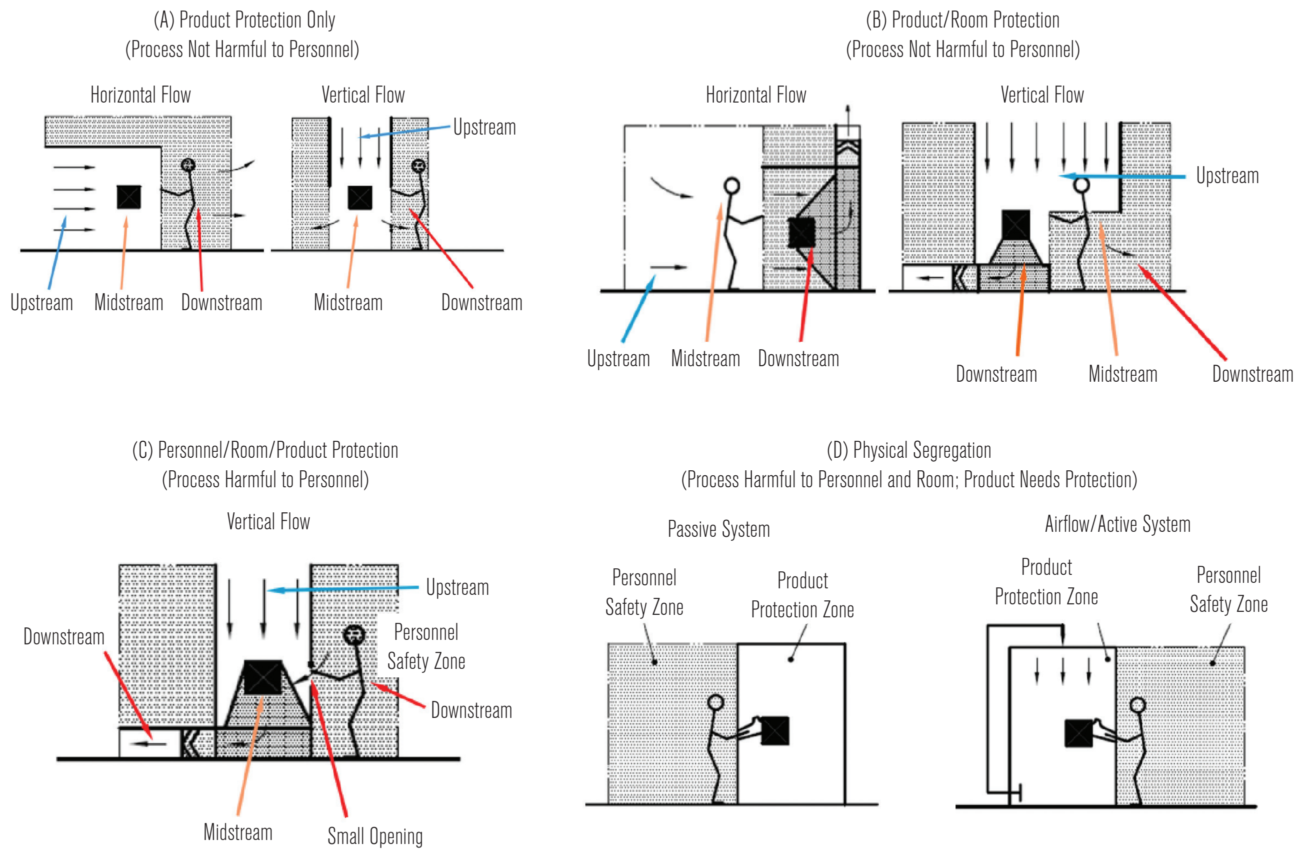
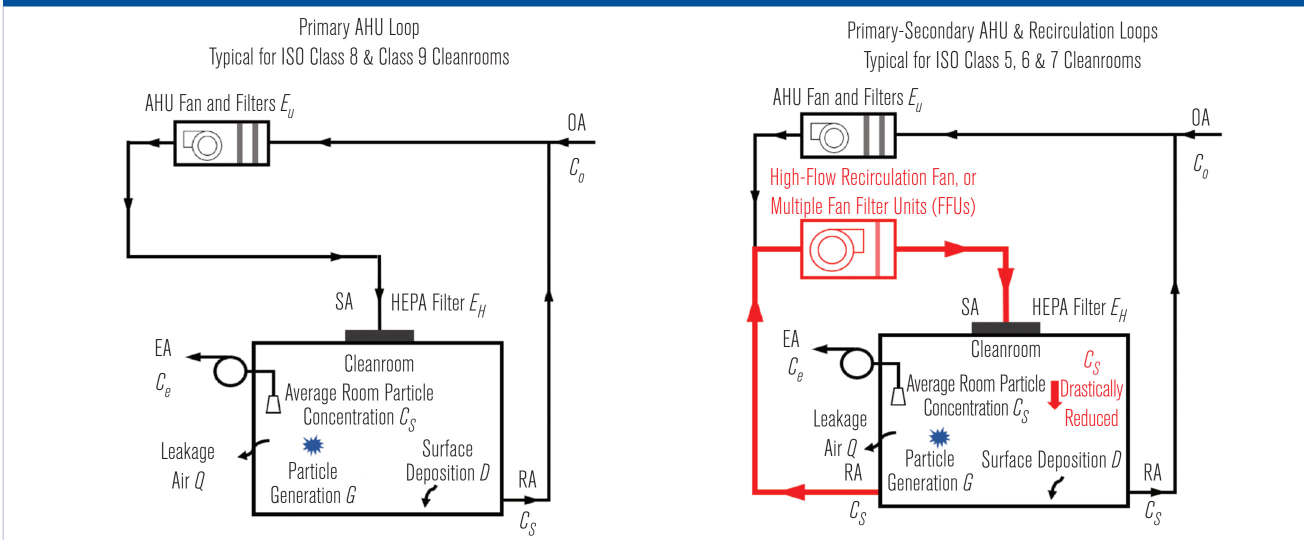


FIGURE 3 Cleanroom AHU loops.[2,3]

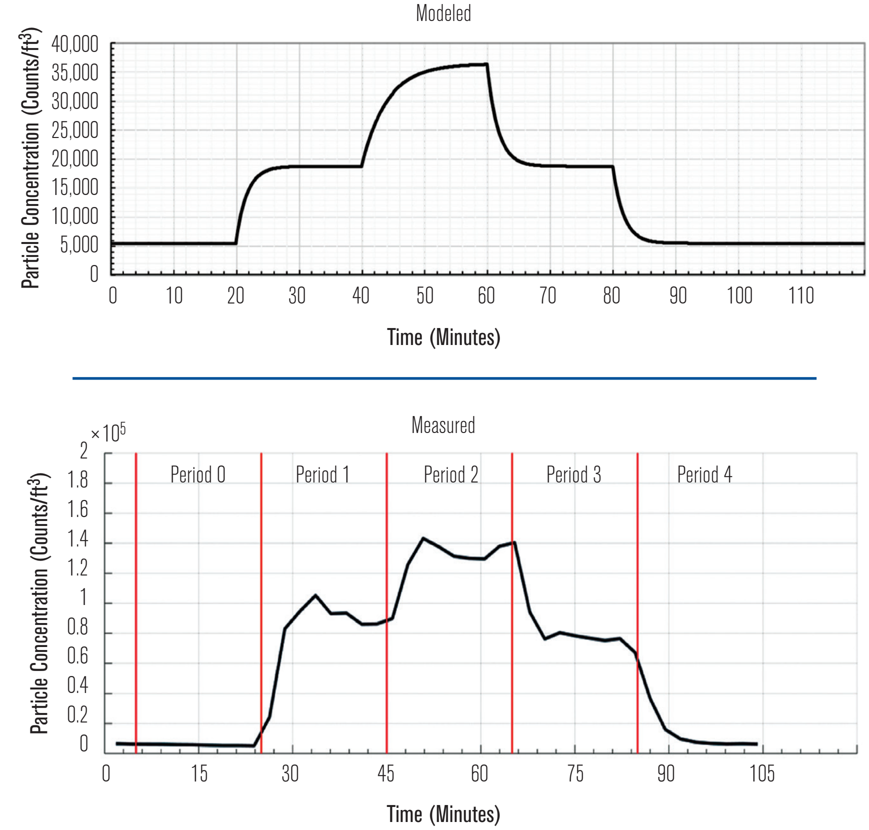


higher levels of dilution or displacement to attain the much lower concentration. A secondary air loop is commonly “added” to offer a higher recirculation flow rate to a cleanroom while the room’s heating/cooling load is decoupled and served from a separate AHU. A 2 ft × 4 ft (610 mm × 1220 mm) fan filter unit (FFU) with electronically commutated motor (ECM) could deliver over 500 cfm (236 L/s) but only consumes 80 W. Using multiple FFUs for recirculation flow can drastically increase ach and decrease room particle concentration, while the primary AHU unit is not necessary to increase its capacity as the heating/cooling loads do not change significantly due to the increase of room recirculation (secondary) rate.

For high-end ISO Class 4, Class 3, Class 2 and Class 1 cleanrooms, primary-secondary is common; sometimes primary-secondary-tertiary in three loops could be necessary as the flow rate is further increased to almost 100% ceiling coverage by HEPA/ULPA filters.

Cleanrooms in all classes may have HEPA-filtered supply air (SA), return air (RA), outdoor air (OA), exhaust air (EA), leakage air (Q), particle generation (G), and surface particle deposition (D). The resulting room concentration is neither uniformly distributed nor well mixed within a room; air is "cleaner" below HEPA filters and "dirtier" near particle emission sources. The average room particle concentration (C_S) is a function of multiple variables.[2,3]

FIGURE 4 (Example) modeled vs. measured room particle concentration under dynamic challenges.



Cleanroom particle concentration (average) value in response to a well-distributed aerosol challenge in multiple periods:

Period 0: No Emission (Background) Period 1: Level-1 Emission (Step Up) Period 2: Level-2 Emission (Step Up)
Period 3: Level-1 Emission (Step Down) Period 4: No Emission (Background)

Room Particle Concentration Models And Contaminant Removal

Theoretical models of cleanroom particle concentration calculation used in the industry today were based on IEST's Recommended Particles IEST-RP-CC012.3;[3] key models were cited and credited from the author's article[2] by IEST. Since the models were based on an assumption that particles behave as air in movement and distribution, a singular correctional factor, either contaminant removal effectiveness (CRE) or another index can be added into the models.

Aerosol particles could suspend in room air for a certain period of time before settling down on surfaces, or be transported along an airstream path surrounding the stream vicinity. When air hits physical obstructions such as equipment or return grille frames, air can turn around and find a passage to exit through return grilles, while the particles traveling with the airstream could lose their momentum and be stopped, trapped and deposited on local surfaces or the floor. Not all particles can exit smoothly through return air; the effectiveness of contaminant removal, which is as important as the more costly air change rate delivery, has been neglected in the HVAC community. A large quantity of supply air pairing with a poor return air passage wastes money! Further study on efficient contaminant-removal mechanisms for various scenarios could lead to a significant reduction of the air change rate requirement.

Figure 4 shows an example between model-predicted versus measured room particle concentration. Theoretical models need to include multiple correctional factors to narrow the gaps between the predicted and measured curves to have predictions to reflect reality, and only then models can be used for actual calculation and CFD analysis.[3]

Demand Based Flow Control

A cleanroom's particle concentration sensed by laser particle sensors or manifold sensing can be used as a feedback signal to control supply flow rate not only to meet a cleanroom's heating and cooling loads, but also to maintain the room's air cleanliness class automatically. The strategy is to modulate the supply rate to maintain the same cleanliness based on real-time particle sensing value; significant fan energy can be saved especially during partial load and unoccupied times.

Conclusions

Cleanrooms' unique HVAC techniques can achieve ultralow airborne contamination to meet industrial specifications and to protect human, room and products in providing much higher air purity and lower contaminant concentrations than commercial spaces.

These techniques include but are not limited to: adding air recirculation loop with ceiling FFU units to deliver a higher air change rate to achieve superb air cleanliness without much extra fan energy; using contaminant source-strength reduction, isolation and removal, plus transmission controls before applying a large quantity of filtered dilution air; arranging cascading airflow direction in up-mid-down streams; applying pressurization and installing anteroom/airlock to reduce external contaminant migration; and applying particle sensor-based VAV demand flow control to prevent airflow oversupply. Engineers could be inspired to imitate some less-intense approaches for commercial applications in achieving enhanced contamination control only if feasible, applicable and cost-effective. Some findings of this article are from the ongoing ASHRAE RP-1604 Research Project.

References

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2. Sun, W., et al. 2010. "Development of cleanroom required airflow rate model based on establishment of theoretical basis and lab validation." *ASHRAE Transactions* 116(1).

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