Designing Clean Room HVAC Systems

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The purpose of the clean room air-conditioning system is to supply airflow in sufficient volume and cleanliness to support the cleanliness rating of the room. Air is introduced into the clean room in a manner to prevent stagnant areas where particles could accumulate. The air must also be conditioned to meet the clean-room temperature and humidity requirements. In addition, enough conditioned makeup air must be introduced to maintain the specified positive pressurization.

This article considers clean-room air-conditioning system design. To simplify the presentation, clean rooms are divided into three general levels of cleanliness: Stringent, Intermediate, and Less Stringent (*Table 1*).

Airflow

The design flow of filtered air through the clean room is highest in Stringent clean rooms and decreases as the requirement for cleanliness decreases. Airflow is usually specified either as average air velocity within the room or as air changes per hour.

The average room air velocity approach typically is used when a full filter ceiling is to be installed. For years, a value of 90 fpm (0.46 m/s) ± 20% has been used to specify the airflow in the cleanest of clean rooms. This was based on the design of the earliest clean rooms built to support the space program during the 1960s and 70s.

In recent years, companies have experimented with lower velocities and have found that airflow velocity specifications ranging from 70 to 100 fpm (0.35 to 0.51 m/s) ± 20% could be successful, depending on the activities and equipment within the room. The higher values are used in rooms with a greater level of personnel activity or particle-generating process equipment. The lower value is used in rooms with fewer, more sedentary, personnel and/or equipment with less particle-generating potential.

Frequently, knowledgeable clients with extensive clean-room experience specify the low-end of the velocity range. Clients and designers new to clean rooms or less confident that a lower velocity will suffice select the higher end of the scale. There is no single value of average velocity or air change rate accepted by the industry for a given clean-room classification. A single exception to this statement is the 90 ± 20 fpm (0.46 ± 0.10 m/s) velocity specified by the FDA for critical pharmaceutical sterile filling areas.

The air change per hour specification is most commonly found in clean rooms of Intermediate or Less Stringent cleanliness. Intermediate clean rooms are usually designed with hourly air change rates between 30 and 160, while Less Stringent clean rooms have hourly air change rates up to 20. The designer selects a value based on his experience and understanding of the particle-generating potential of the client's process. The trend in recent years has been to move toward lower airflow values, as bolder design/build firms and budget conscious end-users successfully experiment with these values.

The Institute of Environmental Sciences and Technology Recommended Practice 12 (IEST-CC-RP.012.1) includes a table with a range of recommended airflow rates for each cleanliness class as does the more recently published ISO 14644-1 Part Four. *Table 1* presents these values. Both are consensus documents that bring together the opinions of clean-room designers, builders, and users to arrive at figures that are known to have worked through the years. All such documents pass the responsibility for specifying parameters onto the shoulders of the "buyer and seller" of the clean room, hence the somewhat cautious wording of the recommendations presented earlier.

Filtration

For many years, the microelectronics industry has driven clean-room technology. The call for higher filter efficiencies has come from this and related industries. The ULPA (Ultra Low Penetration Air) filter with an efficiency of 99.9995% on 0.12 micron particles has been used effectively in the most Stringent clean rooms. Higher efficiency filters are available, but they are costly and have not found widespread use. Efficiencies such as 99.99% and 99.999% are available from a number of manufacturers and have proven to be effective in Stringent clean-room applications.

About the Author

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HEPA (High Efficiency Particulate Air) filters, rated at 99.97% efficiency on 0.3 micron particles, have been the workhorses of the clean-room industry for many years. They are still widely used in the pharmaceutical industry to meet even the most demanding FDA cleanliness requirements.

As filter test instrumentation has matured and smaller particles can be counted with greater accuracy, test data have shown that both ULPA and HEPA filters pass more particles in the 0.1 to 0.2 microns range than any other size. In fact, the filters display their rated efficiency at both 0.12 and 0.3 micron particle size and have a higher efficiency on both larger and smaller particles. For Stringent applications, it is common to see filter efficiency specified based on the most penetrating particle size (MPPS) rather than a specific 0.12 or 0.3 micron size. The MPPS may vary slightly between filter lots. Specifying the desired efficiency at the "worst case" particle size has found favor with some designers and filter manufacturers.

Most Stringent and Intermediate clean rooms are built with the filters in the ceiling. The filters can be installed in groups housed in a proprietary modular pressure plenum system that facilitates installation in the clean-room ceiling. They can also be installed in single filter housings, individually ducted, suspended in an inverted "T" grid support system, and sealed to prevent unfiltered bypass air from entering the clean room. "Stick built" pressure plenums are still used. However, the various modular schemes currently available offer both better air velocity control and better environmental control and have all but replaced the "stick built" design.

The integrated filter/blower unit or fan filter has come into widespread use. In some products the filter is replaceable. In others, the entire module is discarded at the end of its life. They come in various sizes designed to fit into an inverted "T" grid system. Different motor voltages are available to support a variety of electrical design schemes. Some sophisticated control schemes have been devised to monitor individual filter fan operation, record energy usage, signal motor failure, control banks of filter fans, and vary the fan speed for different time of day operation. They have found application in all classes of clean rooms.

The face velocity of ceiling-mounted filters generally can be as high as 130 fpm (0.66 m/s) and as low as 50 fpm (0.25 m/s) depending on the design of the system. Since the system supporting the filters, such as the inverted "T" grid, may occupy as much as 20% of the ceiling area, a 100 fpm (0.51 m/s) filter-face velocity translates into an 80 fpm (0.41 m/s) average velocity at the work surface within the clean room.

Installing HEPA/ULPA filters directly in the ceiling of the clean room is driven by the desire to minimize, if not eliminate, dust-collecting surfaces, such as the inside of ductwork, between the downstream face of the filter and the clean room. Remote mounting of HEPA filters is common in Less Stringent applications since the number of particles that can be contributed by ductwork downstream of the HEPA filters is small as a proportion of the amount that can be tolerated. An exception would be where a standard air-conditioning system with no cleanliness classification is being upgraded to support a clean room intended to carry a cleanliness rating per Federal Standard 209 or ISO

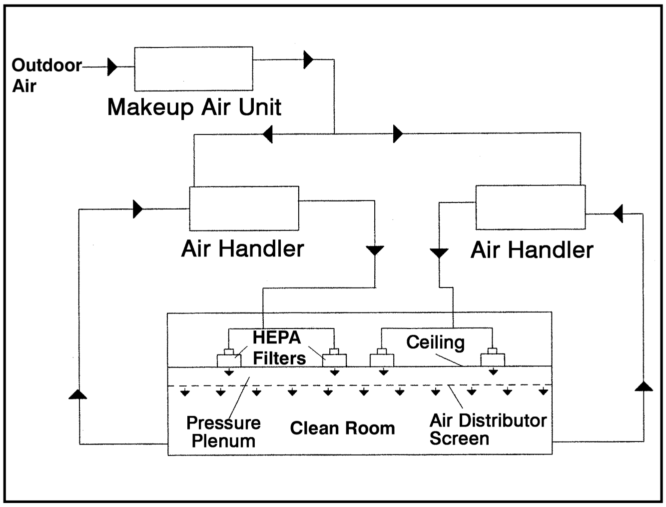

Figure 1: Low-velocity unidirectional flow clean room.

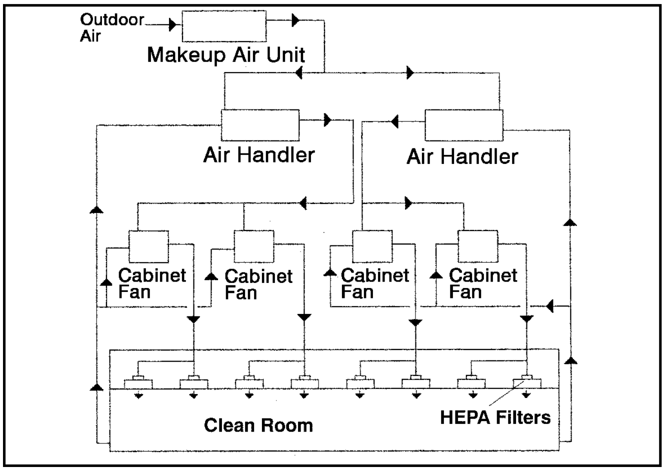

Figure 2: Non-unidirectional flow clean room using recirculating cabinet fans, air handlers and a makeup air unit.

Standard 14644. In that case, all ductwork downstream of the filter should be thoroughly cleaned. Cabinet fans or air handlers with HEPA filter racks on the discharge side are frequently used in Less Stringent applications.

The HEPA filters used in these applications are generally high-velocity filters, based on 500 fpm (2.54 m/s) filter-face velocity, with a pressure drop significantly higher than those used in ceiling installation. A clean 2 ft × 2 ft (600 mm × 600 mm) high-velocity HEPA filter can have a 1.5 in. w.c. (375 Pa) pressure drop at 500 fpm (2.54 m/s). The typical ceiling-mounted clean filter is designed for a pressure drop on the order of 0.5 in. w.c. (125 Pa) at a face velocity of 100 fpm (0.51 m/s).

Room Air Patterns

The air introduced to the clean room, having gone through HEPA or ULPA filters, is essentially free of particles. The air entering the room has two purposes. First, it needs to dilute particle concentrations that may have formed in the room due to personnel or process activity. Second, it needs to entrain such particles in the airstream and carry them from the room.

Three types of airflow are identified.

1. Unidirectional flow (formerly referred to as “laminar flow”), where the air streamlines are essentially parallel to one another.
2. Non-unidirectional flow (formerly “turbulent”), where air streamlines are other than parallel to one another.
3. Mixed flow, where air streamlines may be parallel in one part of the clean room and not parallel in other parts.

Stringent clean rooms are almost invariably designed for unidirectional airflow. This is achieved by providing 100% coverage of the ceiling with HEPA/ULPA filters and installing a raised floor with perforated floor panels. The air moves vertically downward from the ceiling through the perforated floor panels into a return air plenum below the floor. The air then moves laterally to air return ducts at the periphery of the room and eventually to fans for recirculation back to the clean room.

Where the clean space is fairly narrow, on the order of 14 to 16 ft (4.2 to 4.8 m) from wall to wall, the raised floor is often eliminated in favor of low sidewall return grilles. The air will move vertically downward to within 2 to 3 ft (0.6 to 0.9 m) of the floor before splitting and moving toward he sidewall returns. This has proven to be acceptable in many Stringent clean-room applications, particularly when upgrading an existing space with insufficient overhead clearance is encountered.

In a unidirectional clean room, furniture and equipment will affect the airflow pattern. Placing these obstructions in a manner that prevents dead air spaces from developing will minimize their effect on cleanliness.

Non-unidirectional airflow is often used in Intermediate clean rooms. HEPA filters are installed in the ceiling in a pattern that provides fairly uniform coverage. The air moves downward into the clean room. However, the air streamlines are random with no definable pattern. While the air entering the room is essentially particle-free, the clean-room particle counts at critical work surfaces will seek a level based on: the number of particles generated in the clean room; the dilution effect of the clean

ISO Classifications	Federal Standard 209E	Federal Standard 209E	Guideline	Airflow (fpm)	Airflow (ACH)
1	No Equiv.	No Equiv.	Stringent	70–100	
2	No Equiv.	No Equiv.	Stringent	70–100	
3	1	M1.5	Stringent	70–100	
4	10	M2.5	Stringent	70–100	
5	100	M3.5	Stringent Intermediate	70–100	225–275
6	1,000	M4.5	Intermediate	N/A	70–160
7	10,000	M5.5	Intermediate	N/A	30–70
8	100,000	M.6.5	Less Stringent	N/A	10–20
9	No Equiv.	No Equiv.	Less Stringent	N/A	As Req.

Table 1: The new ISO clean-room classifications are shown at left. U.S. Federal Standard 209E classifications in "English" and Metric designations are also shown. The "Guideline" column indicates the three categories described for the purpose of this article. Note that Class 100 may be considered a Stringent clean room when it is designed for unidirectional flow and an Intermediate clean room when it is designed for non-unidirectional flow in non-critical applications. The right-hand columns provide airflow guidelines in feet per minute average room velocity for Stringent clean rooms and air changes per hour for Intermediate and Less Stringent clean rooms.

air change rate; and the speed with which particles are removed from the critical work zone. In general, the higher the air change rate, the cleaner the Intermediate room, but airflow patterns also play a role.

Air return is particularly important in non-unidirectional clean rooms. Sidewall air return grilles are widely used in these rooms. The grilles should be uniformly distributed around the periphery of the room. This can pose a challenge when process equipment is intended to occupy wall space. When possible, the equipment should be moved off the wall to permit air to flow behind it. Equipment can also be raised on a platform (plinth) with air flowing beneath it. In most cases the clean-room designer intends to facilitate movement of particles from a tabletop height work surface to the floor and then laterally to low wall returns. This flow pattern carries the particles out of the room and eventually to filters where they are trapped. Exceptions might involve process equipment that generates particles at a location above a critical work surface. Some sort of high return capture mechanism may have to be designed. Generally, the "high-to-low" flow is suggested.

It is good practice to limit the horizontal distance air must travel to a return in an Intermediate clean room. A horizontal distance of 14 to 16 ft (4.2 to 4.8 m) should be a design goal. Therefore, a room 28 to 32 ft (8.4 to 9.6 m) wide only needs return grilles located in the peripheral walls. The potential for cross contamination caused by particles dropping out of the airstream, or otherwise being attracted to critical surfaces, while traveling long horizontal flow paths suggests this limitation.

For wider rooms, it is common practice to box in support columns and incorporate return grilles and return air ductwork within the box. In the absence of conveniently located columns, a vertical return plenum can be constructed of suitable clean room compatible material.

In Less Stringent clean rooms, with remote-mounted HEPA filters, standard air-conditioning diffusers can be installed in the ceiling. Air patterns similar to those in standard air-conditioned spaces can be created. Low wall returns are suggested to follow the standard clean-room design practice of bringing clean air in high and removing it low. Where ceiling returns are used, there may be areas of high particle count in the clean space, particularly during periods of high activity. Ceiling returns have been used in some Less Stringent clean rooms. Success is related more to the level of particles generated than the ability of the system to remove them.

The mixed-flow approach has been used where critical and non-critical processes are in the same clean space. If space is not available to house critical operations in a separate room, a single clean room can be created with differing zones of cleanliness. Zones are created by adjusting the filter pattern in the ceiling. In a critical area, more filters are installed in the ceiling. In a less critical area, fewer filters are installed. Supply air may have to be canalized downward over the critical zone before it diffuses to the general space. Depending on clean-room ceiling height, a 2 ft (0.6 m) high Plexiglas shield, or even a flexible plastic curtain draped to within 12 to 18 in. (304 mm to 457 mm) of the floor, can be used.

Return air patterns are adjusted by appropriately locating return grilles to accommodate the varying filtered air quantities and to prevent cross contamination. A raised floor with air return plenum would be even more effective. However, it is often precluded by the client's budget, which usually drives the choice of a mixed flow room as a cost-effective solution for extending a client's limited resources.

A shortcoming of non-unidirectional clean rooms is pockets of air with high particle counts. These pockets can persist for a period of time, and then disappear. This is due to currents that are set up within the room due to process-related activity combined with the random nature of the downward airflow. An effort has been made to simulate unidirectional flow by creating a positive pressure plenum below the main clean-room ceiling, then installing an air-diffusion mechanism as a second ceiling. Perforated plastic or aluminum panels have been used, as has a proprietary screening system composed of woven or non-woven fabric.

The result has been flow characteristics approaching unidirectional flow at velocities significantly lower than those seen in Stringent clean rooms. The airflow pattern's piston effect prevents formation of particle-laden pockets and generally results in a more predictable cleanliness level. This performance is achieved at the lower air velocities that are characteristic of the Intermediate and Less Stringent clean-room designs (*Figure 1*).

Sensible Cooling Load

The cooling load sensible heat ratio in most clean rooms exceeds 95%. Cooling is usually required year-round due to the high fan heat contribution to the airstream as well as the heat generated within the clean room by process equipment. The small latent load is generated by personnel. Each clean room is a unique project and should be analyzed carefully to confirm the nature of the cooling load.

In Stringent and Intermediate clean rooms, most of the large amount of air flowing through the room is generally not conditioned. It is recirculated by fans. The conditioning is done by air handlers with sensible cooling coils that draw off a percentage of the total airflow, condition it, and then discharge the air back into the main airstream before it reaches the recirculating fans (*Figure 2*). The temperature of the air entering the Stringent clean room might only be a few degrees cooler than the return air due to the large air volume being cooled. This temperature difference will usually permit ceiling-mounted HEPA/ULPA filters to be used, with downward airflow that does not produce uncomfortable conditions for workers.

In Less Stringent clean rooms the total airflow may, in some cases, be close to that required for a normal cooling application. That is, the air temperature entering the room may be 15°F to 20°F (8.3°C to 11°C) colder than the return air. In such cases, standard ceiling diffusers or other strategies intended to minimize uncomfortable drafts within the room should be used.

Makeup Air

Outside air is required to makeup for the process exhaust and exfiltration that typically occurs in trying to maintain a positive pressure within the clean space. Makeup air is very expensive in that it must be tempered, humidity adjusted, and cleaned before being introduced into the clean room. While makeup air is unavoidable, it should be minimized to the extent possible in the interest of energy conservation and economy.

Clean-room pressures are usually positive relative to unrated areas. Generally, a value of 0.05 in. w.c. (12 Pa) pressure for the clean space relative to unrated areas is recommended. Higher pressures tend to result in whistling noises and make doors difficult to open (or close). In clean suites with multiple cleanliness classes, the trend is to maintain a positive pressure of 0.02 in. w.c. (5 Pa) between adjacent clean spaces of differing ratings, with the higher pressure in the space at the higher cleanliness rating.

The quantity of makeup air can be determined by summing all the process exhaust volumes in the space and then adding two additional air changes per hour. This semi-empirically derived value has proven to be a safe quantity to use to size the makeup air handler. Actual makeup air introduced at any one time will vary depending on door openings, leakage, and actual exhaust in operation.

The makeup air handler must condition the outside air so it is compatible with the clean-room design parameters. This typically requires filtration, pre-heating, cooling, reheating, dehumidification, and humidification.

In Stringent clean rooms, the unit frequently has three stages of filtration, a 30% ASHRAE efficiency pre-filter, a 95% efficiency intermediate filter and a final HEPA filter. Intermediate and Less Stringent clean rooms often have only two stages of filtration, a 30% pre-filter, and a 95% final filter. As the name suggests, the final filter is at the discharge of the unit.

Preheating is commonly provided where the outside temperature falls below 40°F (4°C) in winter. Cooling and dehumidification is accomplished in the cooling coil where the dew point in the clean room is ≥42°F (5.6°C). Since Stringent clean rooms with fully garbed workers may be maintained at a dry-bulb temperature as low as 66°F (19°C), this puts the lower end of effective humidity control through refrigeration alone at about 40% relative humidity. Reheating is required to raise the low temperature coming off the cooling coil after dehumidification. In calculating reheat, the heat added to the airstream by the recirculating fans is taken into account. This can be quite significant in Stringent clean rooms.

Achieving coil temperatures that can produce a room dew point lower than 42°F (5.6°C) can pose problems. When less than 40% RH is required, the common practice is to use a desiccant system of some type.

In the system described here, the makeup air unit provides all the latent cooling and humidification. The assumption is that the properties of the makeup air can be adjusted to accommodate the latent capacity added by the workers and any moisture that penetrates through the clean-room walls. It also assumes that the latent load throughout the facility is more or less uniform. These assumptions should be tested in each application. They depend on the conditions surrounding the clean room, outside air conditions, and any process within the clean room that might add moisture to the airstream.

In smaller clean rooms with low outside air quantity, the sensible cooling air handler described earlier can be designed as a sensible/latent air handler that conditions the makeup air as well as recirculation air. In this case, there is a mixed airstream composed of clean-room air and outside air that must be conditioned. Mixing dampers proportion the volume of each airstream in response to clean-room pressure. As clean-room pressure falls, the outside air damper opens and the recirculating air damper throttles closed. The air from this unit is distributed to the recirculating fans.

In Less Stringent clean-room applications, the total volume of recirculation air may be close to the air volume required for conditioning. In that case, there may be no recirculating fans at all but rather the air handler, or multiple air handlers, condition and recirculate all the air needed by the clean room.

Summary

The trend in clean-room guidelines is to cast the designer in the role of expert "generalist" able to fulfill the wishes of the client, once those wishes are known. The guidelines typically use words such as "subject to agreement between buyer and seller" to draw the client into the decision-making process since there are as many variations on clean-room design as there are designers that create them. The guidelines presented here have proven effective in use and represent the consensus of technical opinion as the author understands it. As with any guidelines, they must be shaped to each situation to accommodate the varying conditions encountered in the field. ●