Performance Evaluation of Cleanroom Environmental Systems

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Biography

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Abstract

This paper presents in-situ measurement results for energy and environmental performance of thirteen cleanroom systems located in the USA, including key metrics for evaluating cleanroom air system performance and overall electric power intensity. Comparisons with the IEST Recommended Practice (IEST-RP-CC012.1) are made to examine the performance of cleanroom air systems. Based upon the results, the paper discusses likely opportunities for improving cleanroom energy efficiency while maintaining effective contamination control. The paper concludes that there are wide variations in energy performance of cleanroom environmental systems, and that performance benchmarking can serve as a vehicle to identify energy efficient cleanroom design practices and to highlight important issues in cleanroom operation and maintenance.

Keywords

Cleanroom, performance, energy efficiency, environmental system, re-circulation air, make-up air, and benchmarking.

Introduction

Effective contamination control is the principal reason to operate a cleanroom. Because the purpose of a cleanroom is to control the concentration of airborne particles to minimize undesired existence of particles inside the cleanroom, and to maintain certain environmental conditions[1], environmental systems (HVAC systems) designed for cleanrooms are extremely energy intensive compared to their counterparts in commercial buildings. Some industries use production metrics such as watts per unit of product, which focus on overall production efficiency but overlook the efficiency of energy intensive environmental systems. Since energy generally represents a significant operating cost for cleanroom facilities, improving energy efficiency in cleanrooms can contribute to significant cost savings. Because the number of cleanrooms in the US and around the world has been growing rapidly in the last decade and involves many industries, improvement in energy efficiency is becoming more important.

Energy intensity varies with the system design, cleanliness levels[2], cleanroom functions, and critical parameter control such as temperature, humidity, etc. According to an earlier study[3], an estimate of cleanroom electricity intensity for the energy use for cooling and fan energy ranged from 159 kWh/ft^2 to 945 kWh/ft^2, corresponding to different cleanroom classes in California. Depending on cleanroom class, fan power intensity ranged from 5 W/ft^2 to 96 W/ft^2. Derived from the data in the study, fan power use for cleanrooms of ISO Classes 3, 4, 5 is the most electricity intensive, and collectively accounts for approximately 80% of the fan power use for cleanrooms of all classes in California. A review of studies on cleanroom costs indicated that energy cost could amount to 65-75% of the total annual cost associated with cleanroom operation and maintenance in Europe[4]. Another study conducted a comprehensive review of strategies for energy benchmarking and specifically addressed issues associated with cleanrooms and laboratory-type buildings[5]. A later study indicated that HVAC energy use accounted for 36-67% of the total cleanroom energy use in three facilities in California[6]. There is, however, a lack of data on the energy performance of actual operating cleanroom environmental systems.

To better understand the energy performance of existing cleanroom environmental systems in various industries, and to identify opportunities in improving energy-efficiency thereby achieving energy savings, it was necessary to obtain field data and to evaluate how real environmental systems actually perform. The data can also help building owners, operators, and designers to compare energy use of their facility to others.

Objective

The objectives of this paper are to 1) present benchmarking results on the environmental energy performance of thirteen cleanroom systems; 2) examine the efficiency performance of air systems as compared to the relevant IEST Recommended Practice CC012.1[7]; and 3) identify opportunities for improving cleanroom energy efficiency while maintaining or improving cleanroom contamination control. This paper focuses on air system performance, and uses important metrics to assess air system performance and process load intensity. The benchmarking results can serve as a vehicle to identify energy efficient design practices, efficiency innovations, and to highlight important issues in cleanroom operation and maintenance.

Approaches

The main approach employed was to conduct field measurements and monitoring in the environmental systems serving cleanrooms. To characterize the physical information of each cleanroom system, related system information was compiled based upon a review of building and system drawings, existing balance reports, vendor submittals, energy management systems, and interviews with building engineers. In addition, physical inspections were carried out to locate field measurement points and to collect monitoring data.

This study includes field measurements and monitoring of air systems in 13 cleanrooms classified as ISO Cleanliness Classes 4, 5 and above[1], which roughly correspond to Cleanliness Classes 10, 100, and above, respectively, in Federal Standard 209E[8]. Because Federal Standard 209E has been cancelled and the industry is in the transition of adopting the ISO cleanliness classification, limited use of the FS209E cleanliness classification is preserved in this paper. Most of the cleanrooms are located in

California in the USA, and the measurements were conducted in 2000 and 2001. This paper will not discuss any climatic impact on system performance due to limited information available.

Relevant metrics were developed to evaluate air system's energy performance for various designs, cleanliness classes, and processes occurring in the cleanroom. The metrics allow direct comparison of energy intensive systems and components based on design or measured data. Specifically, air system efficiency is defined as the airflow rate per unit of total electricity input (cfm/kW). Since cleanrooms are used for many different activities, there are large variations in process loads. Although a portion of the process heat source may be dealt with directly by the chilled water system, its removal by air systems largely influences the cooling requirements for HVAC systems. To compare process load intensity, process load was characterized based upon the process heat output per unit of primary cleanroom floor area (W/ft^2). Table 1 defines key metrics used in this paper.

Measurements and Uncertainty Analysis

The airflow measurement was made by the use of an electronic flow food with backpressure compensation. The flow hood readings represent local density airflow corrected for barometric pressures. The measurement range is 25-25,000 cfm supply with an accuracy of ±3% from 100 to 2,000 cfm[9]. The total flowrate of supply air was obtained by summing the measured airflow rates through all supply outlets in the cleanrooms. The main limitation to this approach is that in some cleanrooms, a small amount of outlets were not physically accessible by the flow hood. In this case, total supply airflow was obtained based upon extrapolating from measured airflows, the actual number of outlets measured, and the total number of outlets in the cleanroom. It was assumed that uncertainty in summing supply airflow rates was primarily due to the bias in measurements, which would be estimated as ±3%. More conservatively, even with a few inaccessible outlets (e.g., a very small portion accounting for 5% of the total outlets) and with airflow variations among all outlets being very small, we might expect a maximum of ±6% uncertainty in some calculated total supply airflow rate.

The electric power measurements and monitoring were made using a portable data logger powered by 12-VDC batteries[10]. The measurement accuracy of electric power and energy is within ±4% with a display range from 1 watt to 60 megawatts (using input ratios). The data logger was installed to take spot measurements of power usage of fans and process under normal operation conditions, and/or to monitor the power usage for a period of time whenever possible. The power usage was observed to be quite constant during the monitoring periods. Given the uncertainties in measured airflow rates and average measured fan power usage, the uncertainty in the measured Re-circulation Air Handler Unit Efficiency is estimated to be about ±8%. If conservatively assuming the uncertainty of estimating floor area as 5% for instance, the uncertainties in the measured power intensity would be approximately ±7%; while the uncertainties in the calculated average cleanroom air velocities and air-change rates would be approximately ±8%.

Table 1. Performance Metrics of Cleanroom Systems

Metrics	Definition	Unit	Uncertainty
Re-circulation Air Handler Unit Efficiency	Recirculated airflow rate per kW of electricity used by all re-circulation air fans	Cfm/kW	8%
Power Intensity for Re-circulation Air Handler Unit	Total fan power of re-circulation air handler unit per unit of primary cleanroom floor area	W/ft^2	7%
Cleanroom Air Change Rate	Cleanroom airflow rate divided by primary cleanroom volume	m^3-air /hr /m^3-space	8%
Average Cleanroom Air Velocity	Cleanroom airflow rate divided by primary cleanroom floor area	fpm	8%
Make-up Air Handler Unit Efficiency	Make-up airflow rate per kW of electricity used by make-up air fans	Cfm/kW	8%
Process Load Intensity	Process load per unit of primary cleanroom floor area	W/ft^2	7%

Results

1. General Description of the Cleanroom Air Systems

This study includes field measurements and monitoring to evaluate the performance of air systems in 13 cleanrooms of various cleanroom cleanliness classes. The cleanroom are mostly located in California. Five of them were ISO Class-4 cleanrooms, and eight of them were ISO Class-5 cleanrooms (including one combined with Class-6).

The majority of the energy use in cleanroom HVAC systems is associated with the re-circulation system and to a lesser degree, the make-up air and exhaust systems. This paper presents the results of benchmarking re-circulation systems and make-up air systems in various cleanrooms. Re-circulation air systems recirculate clean conditioned air through high efficiency particulate air (HEPA) or Ultra Low Penetration Air (ULPA) filters for cleanrooms. Re-circulation systems in this study utilize three common designs: a) Fan-tower with pressurized-plenum (FT-PP); b) Distributed re-circulation (DRC) air handler units with ducted-systems; and c) Fan-filter units (FFU). Make-up air systems provide additional fresh air that is drawn from outdoors to replace air lost through exhaust or leakage and thereby maintain certain cleanroom pressure. In a fan tower system, re-circulation air is discharged into a pressurized plenum-type system or through ductwork to HEPA or ULPA filters in the ceiling. FT-PP systems are often most efficient but also may require additional sound attenuation. This adds to the overall system static pressure, which increases the required fan horsepower. In a DRC system serving a specific area of the cleanroom, the re-circulation air is discharged into an open plenum through multiple mid-sized fan units. They may be connected through ductwork, connected directly to plenum ceiling boxes, or connected directly to HEPA filters in the ceiling. DRC systems generally have large air passageways and have lower static pressures and noise levels compared to other types of systems. In fan-filter unit systems, a small fan is integrated with a HEPA or ULPA filter housing which is typically the same size as a ceiling grid. FFU systems have advantages in redundancy, and ease of design and construction.

2. Energy Efficiency for Re-circulation Air Systems

Table 2 shows the energy efficiency of different types of re-circulation air systems used to recirculate clean conditioned air for five ISO Class-4 cleanrooms, seven ISO Class-5 cleanrooms, and one ISO Class-5/6 cleanroom. Overall, the system efficiency varied dramatically from cleanroom to cleanroom.

Among the five ISO Class-4 cleanrooms, the efficiency of re-circulation air systems ranged from 3,086 to 4,839 cfm/kW. FT pressurized-plenum systems had fan system efficiencies over 3,000 cfm/kW. This was more efficient than the DRC ducted distributed system tested, which was below 2,000 cfm/kW.

Including the Class-5/6 cleanroom, the efficiency of re-circulation air systems serving ISO Class-5 cleanrooms ranged from 1,087 to 10,138 cfm/kW. Among these, energy efficiency of the FT pressurized-plenum systems ranged from 4,831 to 10,138 cfm/kW, which was more efficient than their counterparts for cleanrooms of Class-4 were. This was largely because more space was available for the re-circulation system layout in the Class-5 cleanrooms, thus reducing air resistance in general.

In addition, these FT pressurized-plenum systems were relatively more efficient compared to other types of re-circulation systems (DRC and FFU) serving ISO Class-5 cleanrooms. This was because in general pressure drops along the FT pressurized-plenum system were lower while pressure drops along the DRC air handler units and FFUs were higher. A study shows that on average the energy effectiveness for three types of re-circulation air systems was 0.168 W/cfm for a fan tower (with a pressurized-plenum), 0.202 W/cfm for a distributed RC-AHU, and 0.212 W/cfm for a fan-filter unit[11]. These translate into the energy efficiency metric defined here as the following: 5,952 cfm/kW for the fan-tower (pressurized-plenum), 4,950 cfm/kW for the DRC air handler units, and 4,717 cfm/kW for the FFUs. A state-of-the-art fan-filter unit with an electronically commutated DC motor operates more efficiently (as much as 60 percent) than do models with conventional motors[12].

Compared to these, the fan-filter units and distributed RC-AHUs in this study were rather inefficient in energy performance, ranging from 1,276 to 2,374 cfm/kW (for FFUs), and from 1,087 to 2,214 cfm/kW (for DRC systems). It should however be pointed out that for FFUs, the total fan energy use also includes the fan energy used to transport the conditioned air in addition to the energy use directly by fan-filter units. Although this study did not provide further measurements to identify major reasons for the huge variations in energy efficiency, the lower energy efficiency illustrated in FFU systems was likely due to factors such as inefficient motors, inefficient design, and/or layout of the re-circulate pathways, or some combination of these factors. In contrast, systems with fan tower pressurized plenums were much more efficient.

Table 2. Performance Data of Re-circulation Air Systems

Cleanroom Cleanliness Class (ISO[1])	Cleanroom Cleanliness Class (FS 209E[8])	RC-AHU Airflow Type	RC-AHU Efficiency (Cfm/kW)	RC-AHU Power Intensity (W/ft^2)
Class 4	Class 10	FT-PP	4839	16.3
Class 4	Class 10	FT-PP	3152	37.5
Class 4	Class 10	FT-PP	3301	31.3
Class 4	Class 10	FT-PP	3086	32.9
Class 4	Class 10	DRC	1898	30.5
Class 5	Class 100	FFU	1276	15.6
Class 5	Class 100	FFU	1325	21.6
Class 5	Class 100	FT-PP	7050	2.8
Class 5	Class 100	FT-PP	10138	7.9
Class 5	Class 100	FT-PP	4831	9.5
Class 5	Class 100	DRC	2214	10.9
Class 5	Class 100	DRC	1087	24.1
Class 5/6	Class100/1000	FFU	2374	15.8

3. Energy Efficiency for Make-up Air Systems

Outdoor air supply is needed to make-up exhaust (general exhaust, heat exhaust, process exhaust, etc.) and exfiltration to maintain pressurization associated with the cleanroom. Figure 1 shows the measured energy efficiency of make-up air systems along with the re-circulation air systems of for three ISO Class-4 cleanrooms and eight ISO Class-5 cleanrooms and above. Except for two ISO Class-5 cleanrooms, the energy efficiency of make-up air systems overall was much lower than that of the re-circulation air systems (by a factor of up to 18) serving the same cleanrooms. This was probably because of greater pressure losses along the make-up air pathways, which were likely caused by a combination of longer duct runs, more-confined space available for efficient duct layouts, and less-efficient fans or motors. Including the Class-5/6 cleanroom, the efficiency of make-up air handler units in ISO Class-5 cleanrooms ranged from around 540 up to 1,800 cfm/kW. Unlike re-circulation systems, the make-up air systems efficiency varied less dramatically from cleanroom to cleanroom (by a factor of up to 3 for both cleanliness classes combined). All of these indicate that the energy efficiency of make-up air systems can be improved by integrating mechanical design with architectural design at early stage of the project, and by adopting fans and motors that are more efficient.

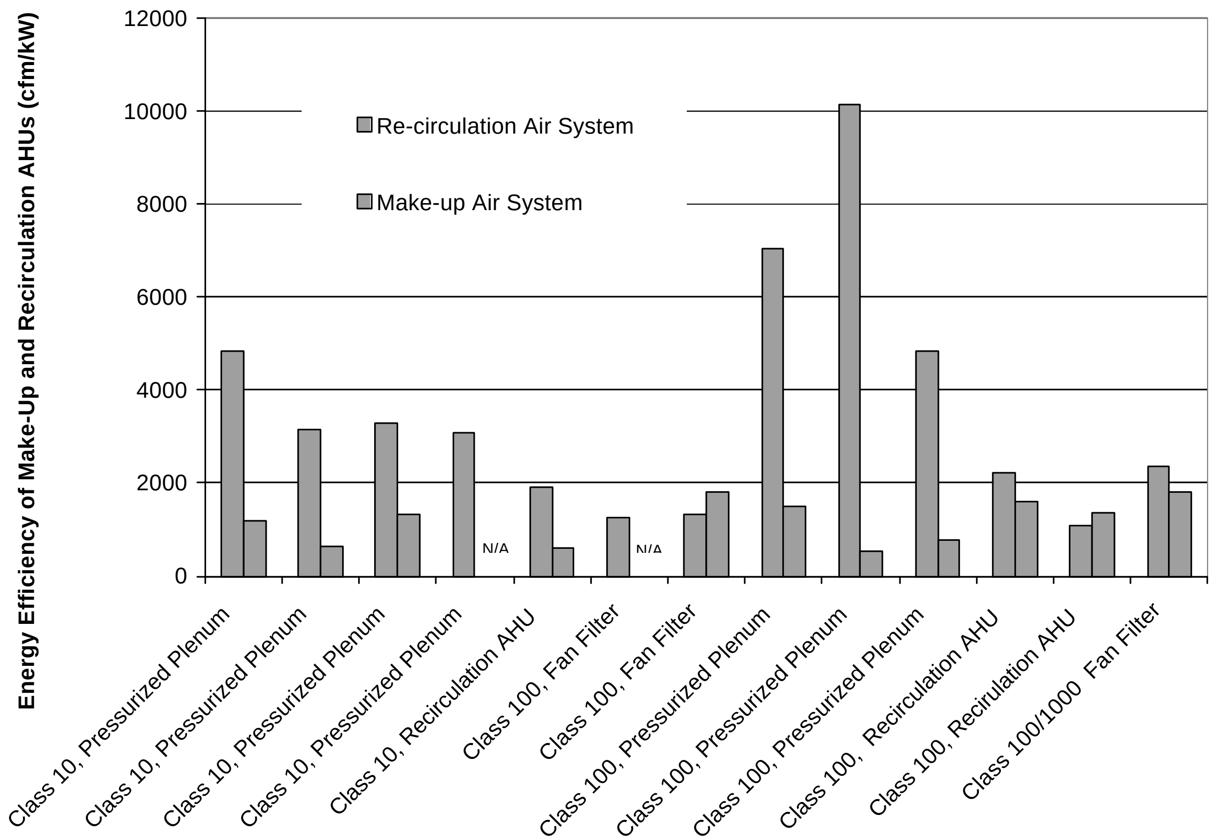

Figure 1. Energy efficiency for make-up air and re-circulation air systems

4. Fan Power Intensity for Re-circulation Air systems

Table 2 also includes the measured fan power intensity of re-circulation air systems for the same five ISO Class-4 cleanrooms and seven ISO Class-5 cleanrooms and one ISO Class-5/6 cleanroom. Overall, fan power intensity varied dramatically from cleanroom to cleanroom. Among ISO Class-4 cleanrooms, fan power intensity of the re-circulation air handler units ranged from approximately 16 to 38 W/ft^2. Including the ISO Class-5/6 cleanroom, the fan power intensity of re-circulation air handler units in ISO Class-5 cleanrooms ranged from approximately 3 to 24 W/ft^2. This indicates that power intensity for various re-circulation air systems for cleanrooms of the same cleanliness class can differ by more than a factor of eight. In ISO Class-5 cleanrooms, FFUs and DRC units on average used more fan power per cleanroom area than pressurized-plenum systems did.

Compared with the same types of systems (e.g., pressurized plenum) for the cleanrooms studied, the measured intensities indicate that re-circulation fan power intensity was greater for higher cleanliness levels, whereas the efficiency decreased accordingly. The findings indicate that it is important for designers *not* to specify higher cleanroom cleanliness than is needed for a specific cleanroom process. Designing and operating a cleanroom with higher cleanliness levels than needed would increase fan power demand and would be less economical to operate.

The electrical demand (kW) for fan power at the same time is, however, largely affected by system design and process equipment needs, in addition to the requirements for cleanroom cleanliness. From the performance data discussed, one can easily see the wide variations of energy efficiency even among cleanrooms of same cleanliness class. This was largely due to the system design and space allocation. Furthermore, the design details and layout alone can sometimes dictate the magnitude of overall air system efficiency, regardless of the cleanroom cleanliness level. For example, the re-circulation system efficiency for cleanrooms with a more stringent cleanliness level (e.g., ISO Class-4 with a distributed re-circulation system) turned out to be more efficient than those with lower cleanliness levels (e.g., ISO Class-5 with a distributed system). This confirms that air system design and space allocation can play a significant role in affecting the system efficiency. The implications from the findings for cleanroom system design are that carefully reducing resistance in the air path throughout air systems can lower pressure drops, and thus require less power and energy to recirculate the air needed to maintain contamination control. From a design point of view, the planning and eventual design of the cleanroom should provide necessary adjacencies and space for efficient air systems and components.

5. Process Loads

Cooling load required to remove process heat is one of the major considerations during the design and operation of HVAC systems. The amount of process load varies significantly from cleanroom to cleanroom. How to estimate process loads in order to accurately size HVAC systems often presents a design challenge. These systems are frequently oversized due to inaccurate heat load or load diversification assumptions. A portable power data logger was used to measure electric power of process tools in the cleanrooms. The spot measurements usually lasted for a short period of time during normal operation, for which the power usage was considered relatively constant. Figure 2 illustrates the measured process load intensity within some of the cleanrooms. Depending upon the process activities, the process load intensity ranged from 4 to 26 W/ft^2 among six ISO Class-5 cleanrooms, and from 36 to 49 W/ft^2 in two ISO Class-4 cleanrooms. These were generally quite low compared to many cleanrooms that are designed for design load intensities between 75 and 125 W/ft^2.

While the magnitude of process loads is dependent on cleanroom activities, the measured results suggest a strong likelihood that process loads were often over-estimated and that HVAC systems have been commonly over-sized. Although over-sizing may be intentional for additional reasons such as the provision for future expansion, reliability, etc., tendencies to add extra conservatism in the design process often result in extra energy waste. The result shown above confirms that process generated heat load tends to be over-estimated in practice and therefore HVAC systems are oversized. The design implication from this benchmarking analysis is that it is necessary and critical to have more accurate estimates of process load for designing an energy efficient environmental system.

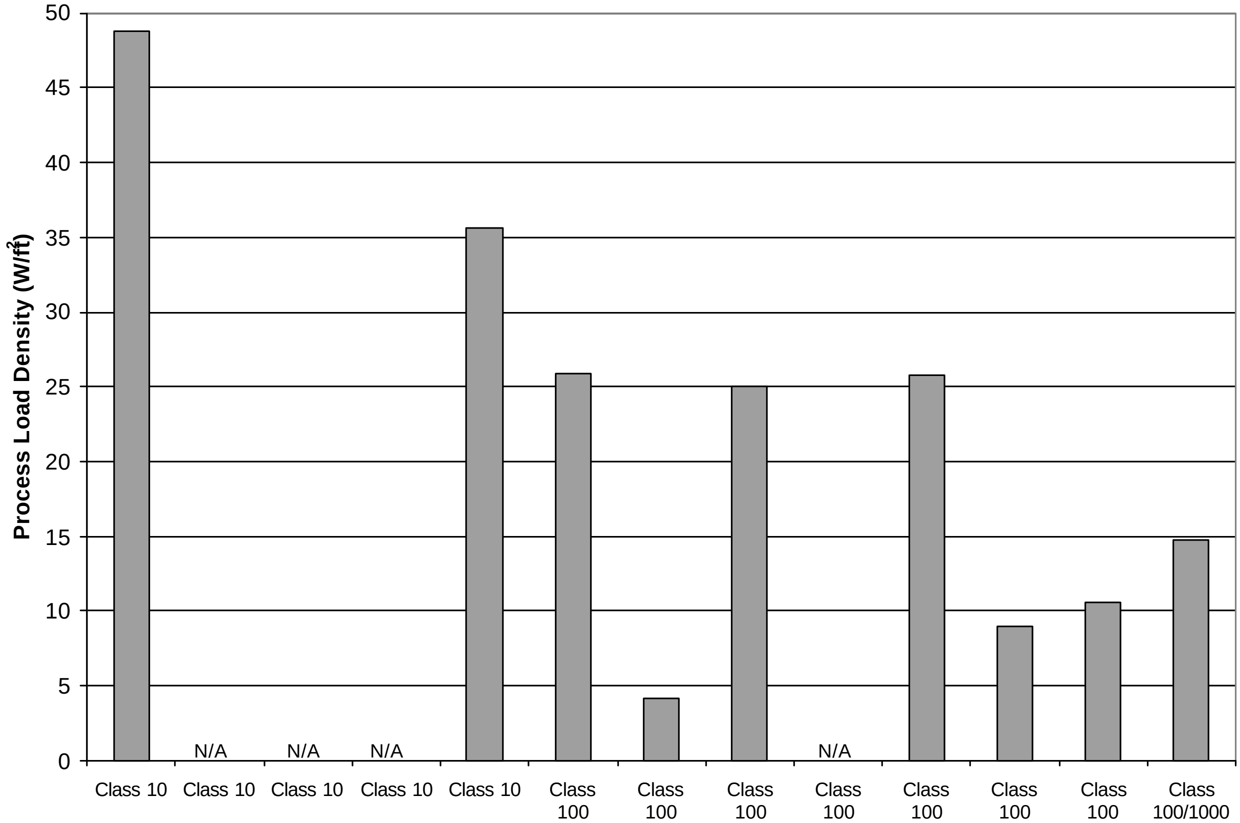

Figure 2 Cleanroom process load density (W/ft^2)

6. Cleanroom Air Change Rates and Average Air Velocities

Simply to relate a cleanliness class level to a specific cleanroom air velocity is a prohibitively complex task due to the number of factors involved. For example, the operating protocol, flow direction, filter performance, equipment and space configuration all have direct or indirect impact on cleanliness level given the same cleanroom air velocity. Unfortunately, there is a lack of scientific basis for determining an optimal cleanroom air change rate.

The Institute of Environmental Science and Technology recommends a range of air change rates between 300 and 540 m^3-air/hr·m^3-space for ISO Class-4 (Class-10) cleanrooms for a unidirectional airflow pattern[7]. The air change rates correspond to cleanroom air velocities between 50 and 90 fpm (or 0.25-0.46 m/s) based upon a ceiling height of 10 ft and full ceiling coverage. Similarly, the IEST also recommends a range for air change rates between 240 and 480 m^3-air/hr·m^3-space for ISO Class-5 (Class-100) cleanrooms, which correspond to cleanroom air velocities between 40 and 80 fpm (or 0.20-0.41 m/s) for any airflow pattern (unidirectional, non-directional, and mixed)[7]. These ranges were originally established based on design of earlier cleanrooms built to support the space program before the 1970s. ASHRAE[13] indicates that circulation rates around 90 cfm per square foot, which equals cleanroom air velocities of 90 fpm (or 0.46 m/s) on average for full ceiling coverage, are usual for ISO Class-5 (Class-100) or cleaner cleanrooms. A recent study[14] recommended 70-100 fpm for cleanrooms of ISO Class-1 through 5, and provided a low range of air change rate (up to 275 m^3-air/hr·m^3-space) for ISO Class-5 through 8. Apparently, there have been conflicting guidelines and acceptable ranges, however, none of the above provided a scientific basis for the recommendations. In practice, acceptable contamination levels have been achieved with either significantly lower or higher than recommended air change rates. There is some confusion among designers and operators in use of recommendations or guidelines, rules of thumb, and their actual operating experience.

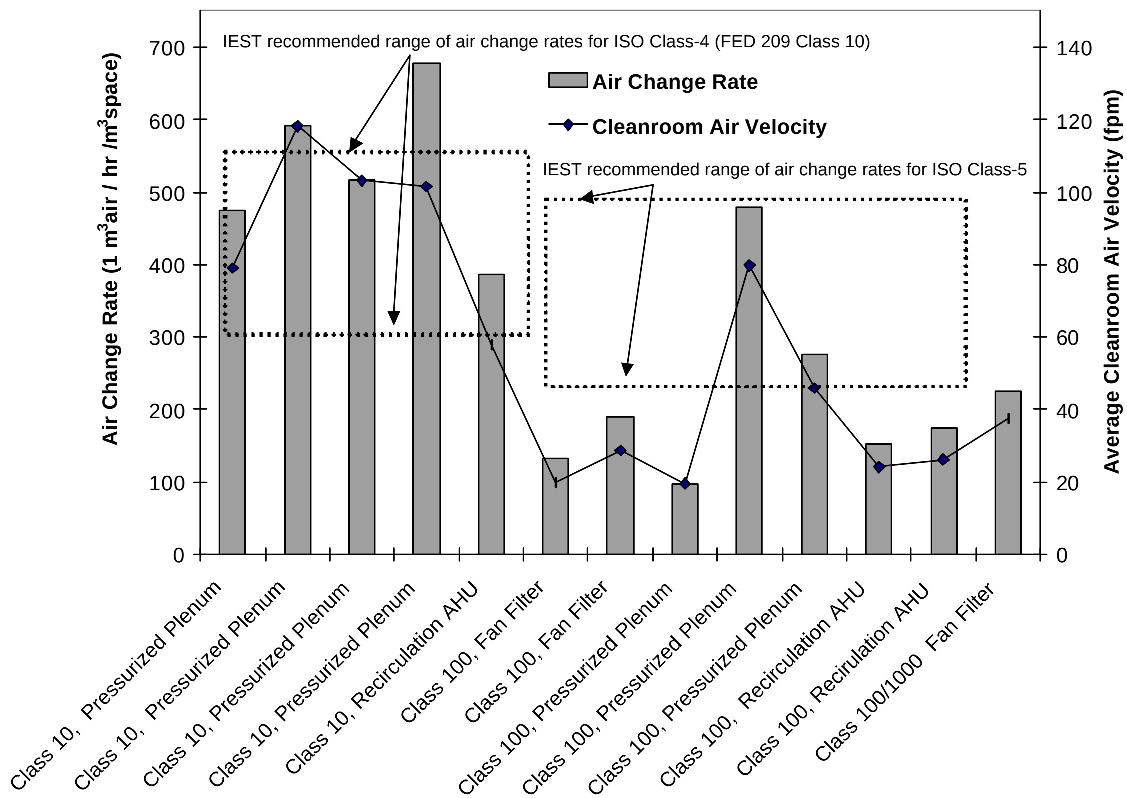

Figure 3. Actual air change rates and cleanroom air velocities as compared to IEST recommended values[7]

The in-situ measurements provide data to indicate how the re-circulation system actually performed. Figure 3 shows the actual air change rates and average air velocities for the cleanroom measured. For the five cleanrooms of ISO Class-4 (Class-10), the measured air change rates were 385, 474, 516, 591, and 678 m^3-air/hr·m^3-space, respectively, corresponding to average air velocities between 58 fpm (0.30 m/s) and 118 fpm (0.60 m/s). This indicates that there was a large variation in re-circulation air supply among different systems, depending on design, layout, and cleanroom activities. Obviously, some of these exceeded higher limit that IEST recommended. Energy saving opportunities might well exist in the meanwhile. For example, reducing the re-circulation air supply by 10% and 20% for the cleanrooms with air change rates of 591 and 678 m^3-air/hr·m^3-space, respectively, could bring down the air change rates below or around 540 m^3-air/hr·m^3-space, which is near the upper limit recommended by IEST for Class-4 cleanrooms. The reduction of airflow rates would then in theory curtail re-circulation fan power by up to 30-50% while complying with the recommended air change rates. In addition, the decrease of fan power use to re-circulate cleanroom air would also reduce the overall cooling load, which would otherwise induce extra heat generated from fan operation.

For the ISO Class-5 cleanrooms, the measured air change rates ranged from 98 up to 479 m^3-air/hr·m^3-space, corresponding to average air velocities between 20 fpm (0.10 m/s) and 80 fpm (0.40 m/s). The majority of the air change rates fell below the recommended lower limit of 240 m^3-air/hr·m^3-space. Although generalization of these findings may be premature based upon the limited number of cleanrooms tested, these findings indicate that there were practical opportunities in certain ISO Class-5 (Class-100) cleanrooms to control airflow below the IEST recommended range of 240 to 480 m^3-air/hr·m^3-space. This also indicates that certain cleanrooms may have particular challenges in producing airflows lesser than the typical range recommended by IEST.

Conclusions

Benchmarking energy performance of mechanical systems and components provides rich information on the system and component performance. Analysis of energy metrics can provide better understanding of system performance, and can suggest energy efficient design practices and long-lasting energy-saving opportunities in cleanrooms. The energy performance evaluation can help to prioritize measures to achieve improvements in system energy efficiency. Specifically, the following are the major conclusions.

- Energy efficiency and fan-power density for re-circulation air systems and make-up air systems varied widely, even among cleanrooms of the same cleanliness classes. We have found potential energy savings opportunities by reducing circulation airflow rates while still meeting the air change rates recommended by IEST. In addition, the decrease of fan power needed to recirculate cleanroom air will also reduce the overall cooling load, which would otherwise introduce extra heat from fan operation. Like optimizing system design and components, carefully arranging system and process layouts can have lasting and benign impact on energy use of air systems.
- These findings may indicate that the operating air change rates required for the ISO Class-5 (Class-100) cleanrooms tested in this study were less than the 240 to 480 m^3-air/hr·m^3-space as recommended by IEST.
- In general, air systems with lower pressure drops (lower resistance to flow) along the return air paths have higher efficiency (cfm/kW) than those with higher air pressure drops. Fan-tower type re-circulation systems with a pressurized plenum providing air to the cleanroom ceiling filters usually result in better efficiency than using separate ductwork to each of the ceiling filters. From a design point of view, the planning and design of the cleanroom systems should provide necessary adjacencies and space for efficient air systems and components.
- The benchmarking analysis provides actual data on process loads that were considerably below typical design values used by designers. This suggests that it is necessary and important for designer to obtain more accurate process loads and their diversification; and to avoid oversizing HVAC systems as a result.

Recommendations

To maximize the usefulness of benchmarking efforts, it will be necessary to obtain more data by benchmarking additional cleanrooms and by integrating available measured field data. Once a statistically sound dataset is available, building operators will be able to compare performance of their cleanroom facilities with others. Future research may include investigations of continuous energy performance as compared to the design intent. In addition, there is a need to develop a benchmarking tool that allows computer interface to compare cleanroom energy performance to a large sample of similar cleanrooms. This will be helpful for identifying good design practices and potential energy-saving opportunities. The findings of lower cleanroom air change rates in actual cleanrooms than those recommendations specified by IEST, ASHRAE, and other literatures indicate that reviewing those air change recommendations to include energy considerations and associated challenges may be useful.

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