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Abstract

By developing metrics for evaluating cleanroom air system performance and overall load intensity, this paper provides energy benchmarking results for thirteen cleanroom environmental system performance, and identifies opportunities for improving cleanroom energy efficiency while maintaining or improving cleanroom contamination control. Comparisons with IEST Recommended Practice are made to examine the performance of cleanroom air systems. These results can serve as a vehicle to identify energy efficient cleanroom design practices and to highlight important issues in cleanroom operation and maintenance. Results from this study confirm that there are opportunities in improving energy efficiency of cleanroom environmental systems while maintaining effective contamination control.

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/ft² to 945 kWh/ft², corresponding to different cleanroom classes in California. Depending on cleanroom class, fan energy intensity ranged from 5 W/ft² to 96 W/ft². Derived from the data in the study, we estimate that fan energy use for cleanrooms of ISO Classes 3, 4, 5 is the most electricity intensive, and collectively accounts for approximately 80% of the fan energy use for cleanrooms of all classes. 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. This data also enable building owners, operators, and designers to compare energy use of their facility to others.

Objective

The objectives of this paper are to 1) present energy benchmarking results for environmental system performance related to thirteen cleanrooms; 2) examine the performance of air systems as compared to relevant IEST Recommended Practice^[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, we also compiled related system information 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.

We selected cleanrooms of different cleanliness classes, which were likely to be the most energy intensive HVAC systems serving cleanrooms. Specifically, this study includes field measurements and monitoring of air systems in 13 cleanrooms classified as ISO Cleanliness Classes 4, 5 and above^[1], which respectively correspond to Cleanliness Classes 10, 100, and above in Federal Standard 209E^[8]. Because Federal Standard 209E has been recently cancelled and the industry is in the transition of adopting the ISO cleanliness classification, we preserve limited use of the FS209E cleanliness classification in this paper. After the on-site measurements were completed, performance data were entered into a database, which was used for further analysis.

We develop relevant metrics 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, we expected wide variations in process loads. Process heat loads and its removal by air systems largely influences the cooling load dealt by HVAC systems. A portion of the process heat load may also be accommodated directly by the chilled water system. To compare process load intensity, process load was characterized based upon the process heat output per unit of primary cleanroom floor area (W/ft²). **Table 1** defines key metrics used in this paper.

Table 1. Performance Metrics of Cleanroom Air Systems and Process Load

Metrics	Definition	Unit
Re-circulation Air Handler Unit Efficiency	Recirculated airflow rate per kW of electricity used by all re-circulation air fans	Cfm/kW
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
Re-circulation Air Change Rate	Re-circulation airflow rate divided by primary cleanroom volume	1/hr
Average Cleanroom Air Velocity	Re-circulation airflow rate divided by primary cleanroom floor area	fpm
Make-up Air Handler Unit Efficiency	Make-up airflow rate per kW of electricity used by make-up air fans	Cfm/kW
Process Load Intensity	Process load per unit of primary cleanroom floor area	W/ft ²

Results

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 three cleanroom cleanliness classes. 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 re-circulate 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. For cleanrooms that generate toxics or hazardous materials that need to be removed to ensure cleanliness, health, and safety,

building codes require exhausting minimum amounts of air from the cleanroom, which must then be replaced through the make-up air system. For these applications, significant quantities of make-up air are required.

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.

Performance of Re-circulation Air Systems

Circulation Energy Efficiency for Re-circulation Air Systems

Table 2 shows the energy efficiency of different types of re-circulation air systems used to re-circulate 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.

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

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^[9]. 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^[10].

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). We should however point 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. Overall, the low energy efficiency illustrated was due to a combination of inefficient motors and inefficient design or layout of the re-circulate pathways. In contrast, systems with fan tower pressurized plenums were much more efficient.

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/ft². 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/ft². 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.

Re-circulation Air Change Rates and Cleanroom 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 re-circulation air change rate.

The Institute of Environmental Science and Technology recommends a range of air change rates between 300 and 540/hr 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 0.254-0.457 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/hr for ISO Class-5 (Class-100) cleanrooms, which correspond to cleanroom air velocities between 40 and 80 fpm (or 0.203-0.406 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^[11] indicates that re-circulation rates around 90 cfm per square foot, which equals cleanroom air velocities of 90 fpm (or 0.457 m/s) on average for full ceiling coverage,

are usual for ISO Class-5 (Class-100) or cleaner cleanrooms. A recent study^[12] recommended 70-100 fpm for cleanrooms of ISO Class-1 through 5, and provided a low range of air change rate (up to 275/hr) 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 guideline. 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 guidelines, rules of thumb, and their actual operating experience.

The in-situ measurements provide data to indicate how the re-circulation system actually performed. **Figure 1** shows the actual air change rates and average air velocities for the cleanroom measured. For the five cleanrooms of ISO Class-4 (Class-10), we have measured the air change rates at 385, 474, 516, 591, and 678/hr each, corresponding to average air velocities between 58 fpm (0.3 m/s) and 118 fpm (0.6 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/hr, respectively, could bring down the air change rates below or around 540/hr, 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/hr, corresponding to average air velocities between 20 fpm (0.1 m/s) and 80 fpm (0.4 m/s). The majority of the air change rates fell below the recommended lower limit of 240/hr. Although generalization of these findings may be premature based upon the limited number of cleanrooms tested, the IEST recommended range of 240 to 480/hr for all ISO Class-5 (Class-100) cleanrooms appears to require more re-circulation airflow than is needed.

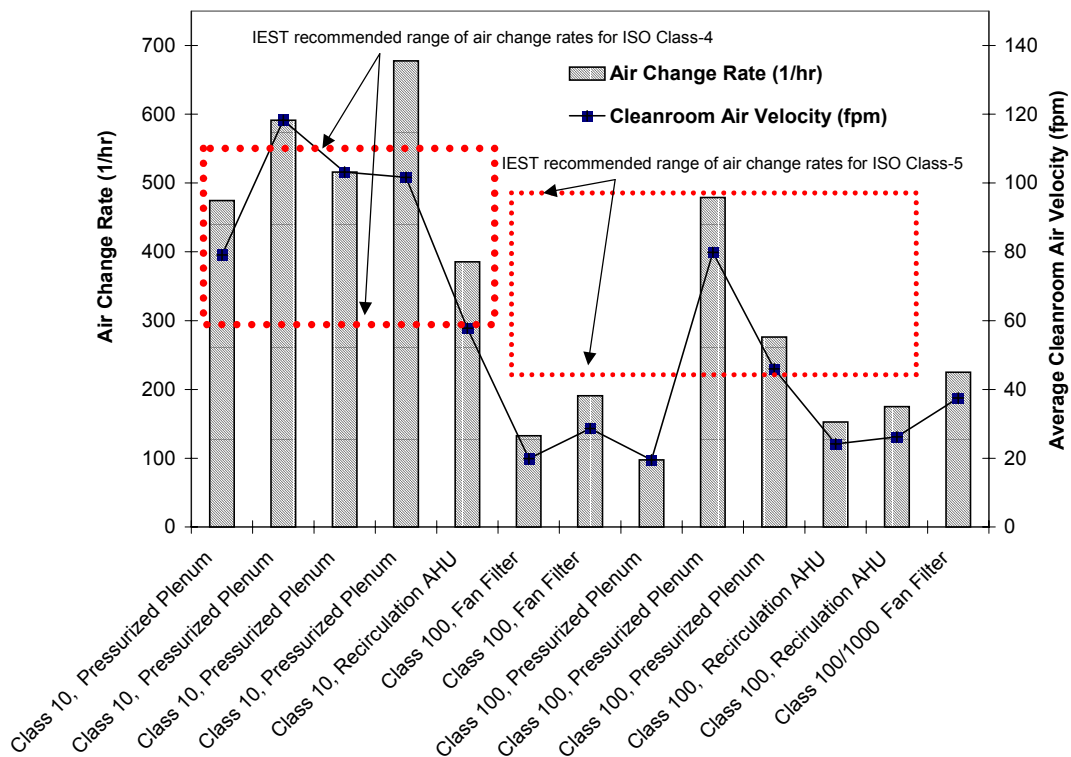


Figure 1. Actual re-circulation air change rates and cleanroom air velocities as compared to IEST recommended values^[7].

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 2 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 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.

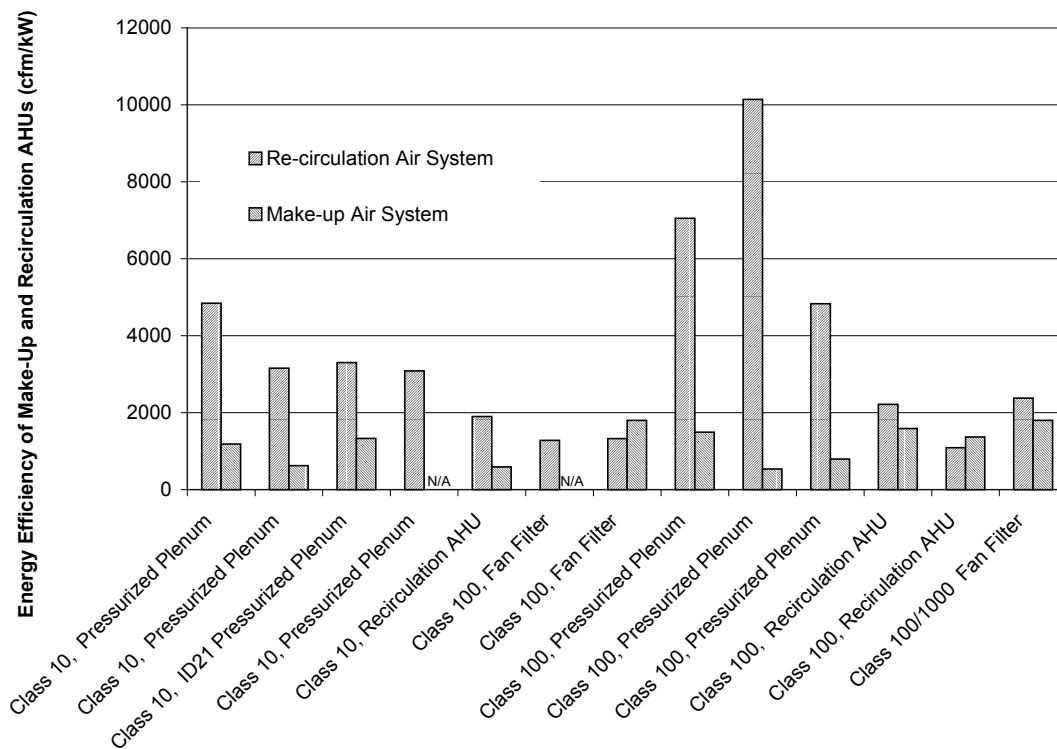


Figure 2. Energy efficiency for make-up air and re-circulation air systems.

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. We measured energy use by process tools in the cleanrooms tested. **Figure 3** 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/ft² among six ISO Class-5 cleanrooms, and from 36 to 49 W/ft² 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/ft².

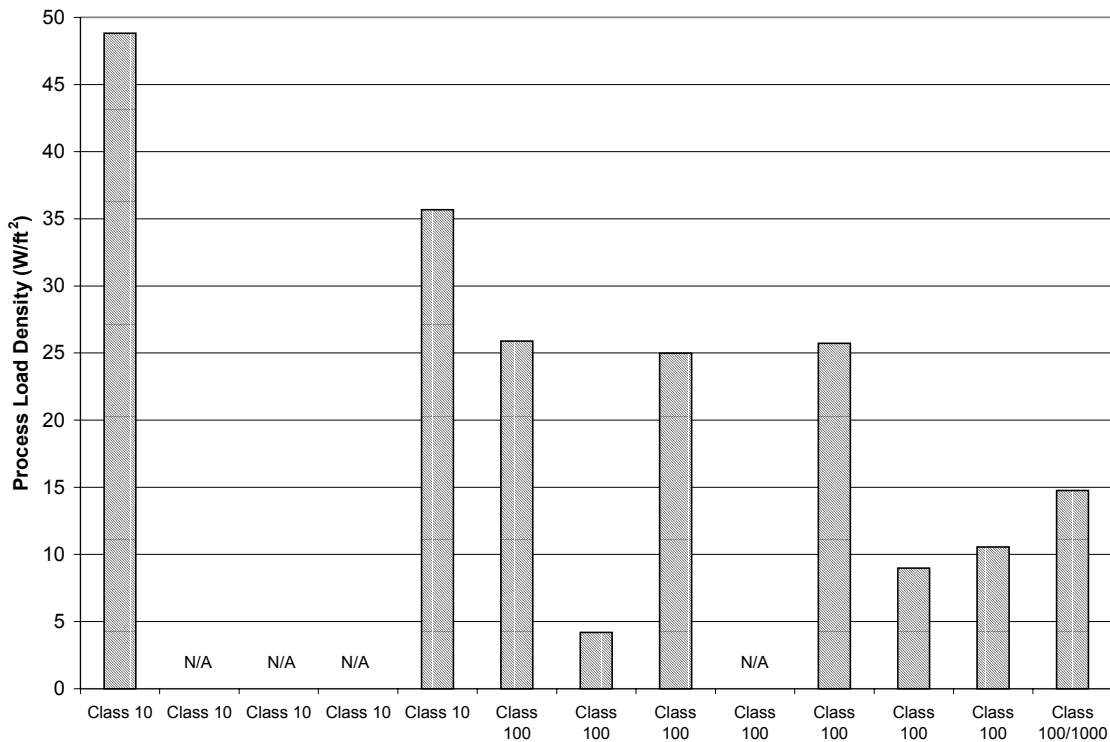


Figure 3 Cleanroom process load density (W/ft²).

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 oversizing 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 an energy efficient system design.

Discussion

Cleanroom HVAC systems account for a large percentage of the energy budget. Depending on cleanroom cleanliness requirement, cleanroom size, system design and utility rates, the cost may vary significantly. In this study, we tested cleanrooms with various cleanroom areas, including some over 20,000 ft². To illustrate the cost impact of an efficient re-circulation system, we looked at the cost difference for cleanroom with an assumed floor area of 20,000 ft², operating 24 hours per day for the whole year (8,760 hours), and an electricity cost of \$0.065 per kWh. By comparing the various power densities of the benchmarked re-circulation systems for a cleanroom of 20,000 ft², this amounts to an annual kWh cost alone of up to 0.43million US dollars, as shown in **Figure 4**. **Figure 4** also indicates that even a slight decrease in re-circulation fan power for energy intensive cleanrooms, which could be realized through careful space planning, design, operation, and control, would result in considerable cost reduction in operating the cleanrooms.

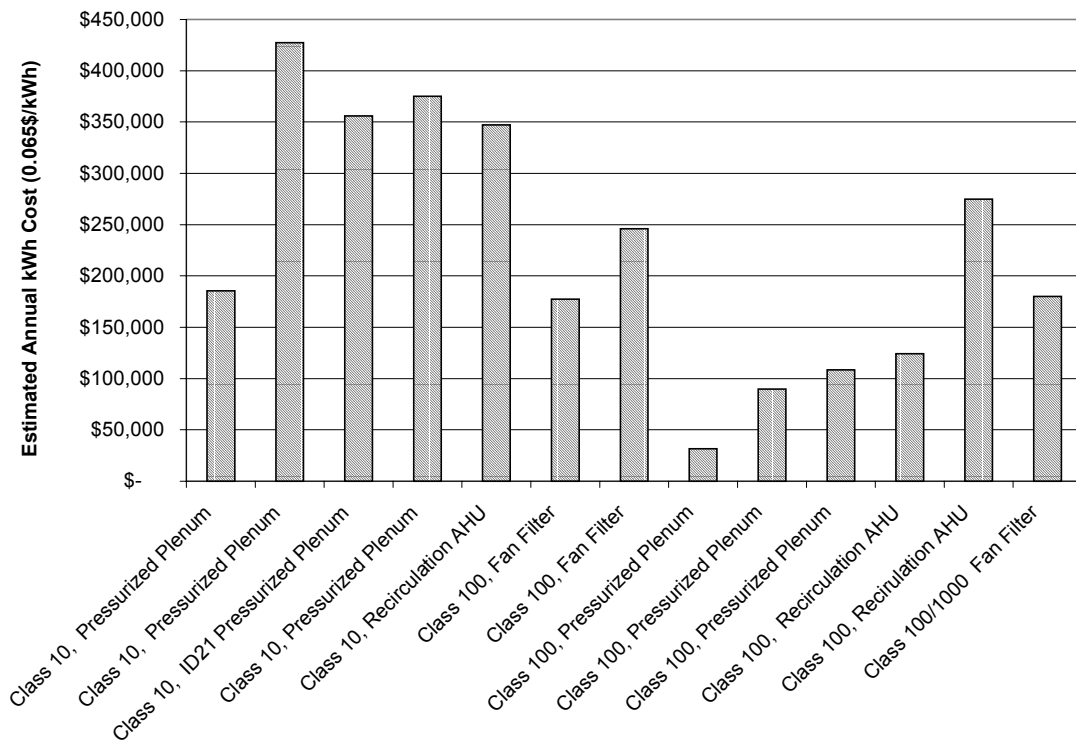


Figure 4 Annual kWh cost of re-circulation air systems for a 20,000 ft² cleanroom.

To determine which air management system is the best selection for a given cleanroom application, there is no direct or simple answer. The key is that designers should carefully consider initial cost, operating cost, process load, and requirements for cleanroom performance and contamination control. For example, the most efficient pressurize-plenum may require additional space. It may also require noise control, which would increase air system static pressure and thus increase the fan power. So comparing these undesired consequences against the efficiency gains from the selection of an efficient plenum system is the challenge. Another example is that fan-filter units exist that are more efficient than those tested in the study. They come with electronically commutated DC motors and can thereby significantly reduce the operating cost over their lifetime. Currently there is no standard comparison data however to allow designers and owners to easily compare performance of these units. This type of fan-filter unit requires larger air passageways and larger cooling coil surfaces in the re-circulation path in order to reduce air friction, however.

The appropriate amount of re-circulation airflow is critical to the satisfactory performance of cleanroom environmental systems as well as effective contamination control. Apparently, there is a need to further examine the scientific basis for appropriate ranges of air change rates and corresponding average cleanroom air velocities currently recommended by IEST. It is recommended that the guidelines be re-examined based upon scientific studies addressing the factors that affect yields in cleanrooms such as protocol, air turbulence, human occupants, molecular contamination, filtration, and their impact on various activities. This would help cleanroom designers and operators achieve highly performing and reliable cleanroom systems.

Conclusions and Recommendations

Benchmarking energy use of mechanical systems and components provides rich information on the system and component performance and can be used as a baseline for tracking energy performance over time. This provides an effective way to understand energy end use in complex cleanroom facilities. The energy performance evaluation can help to prioritize measures to achieve improvements in system energy efficiency. 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. Specifically, the following are the major conclusions and recommendations discussed in this paper:

- 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 re-circulation airflow rates while still meeting the recommended air change rates specified 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.
- The range for air change rates from 240 to 480/hr recommended by IEST for ISO Class-5 (Class-100) cleanrooms tested in this study appears to require more airflow than needed. There is also a need to further examine the scientific basis for the IEST recommended air change ranges for cleanrooms of different cleanliness classes.
- 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.
- To determine which air management system is the right choice for an application, there is no direct and simple answer. The key is that designers should compare and consider initial cost, operating cost, process load, and requirements for performance and control. In particular, if applying fan-filter units, caution should be made to make sure that the state-of-the-art techniques are employed.
- The benchmarking analysis provides actual data on process loads that were considerably below typical design values developed by designers. This suggests that it is necessary and important for designers to obtain more accurate process loads and their diversification; and to avoid oversizing HVAC systems as a result. Improvement in energy efficiency in cleanroom systems while maintaining or improving contamination control will benefit industries by creating immediate capital cost savings as well as overall life-cycle savings, thus improving productivity and contributing to power reliability.

To maximize the usefulness of benchmarking efforts, it will be necessary to obtain more data by benchmarking additional cleanrooms and/or 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 an end-user's self-benchmarking tool that allows computer interface to compare cleanroom energy performance to a large sample of similar cleanrooms. This will be useful for identifying good design practices and new energy-saving opportunities.

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