Efficient Airflow Design for Cleanrooms Improves Business Bottom Lines

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Biography

Dr. Tengfang Xu is a project manager and researcher in the Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory (LBNL), Berkeley, California. He obtained his BS and MS degrees from Tsinghua University, Beijing, and a Ph.D. from the UC-Berkeley. He is a licensed Professional Engineer (PE) in California with fourteen years of research and consulting experience in indoor environment, energy, human factors, and building systems. He is a senior member of the Institute of Environmental Sciences and Technology (IEST), and serves as a Technical Editor for the *Journal of the IEST*. He is also a committee member in IEST's Working Group 12 (Considerations in Cleanroom Design) and Working Group 23 (Microorganisms in Cleanrooms).

Abstract

Based on a review of airflow design factors and in-situ energy measurements in ISO Cleanliness Class-5 cleanrooms, this paper addresses the importance of energy efficiency in airflow design and opportunities of cost savings in cleanroom practices. The paper discusses design factors that can long lastingly affect cleanroom system performance, and demonstrates benefits of energy efficient cleanroom design from viewpoints of environmental control and business operations. The paper suggests that a high performance cleanroom should not only be effective in contamination control, but also be efficient in energy and environmental performance. The paper also suggests that energy efficient design practice stands to bring in immediate capital cost savings and operation cost savings, and should be regarded by management as a strategy to improve business bottom lines.

Keywords

Cleanroom, contamination control, airflow, design, operation, maintenance, high performance, energy efficiency, cost savings, return of investment, business bottom line

Introduction

Large amount of cleaned air is normally required to remove or dilute contaminants for satisfactory operations in mission-critical cleanroom environment across different industries. Cleanroom environmental systems, specifically the HVAC systems, which are used in semiconductor, pharmaceutical, and healthcare industries, are very energy intensive. There is a tendency in cleanroom design and operation, however, to provide excessive airflow rates by HVAC systems, largely due to design conservatism, lack of thorough understanding in airflow requirements, and more often, concerns such as cleanliness reliability, design and operational liabilities. A combination of these factors can easily result in over-sizing of air systems. Energy use of cleanroom environmental systems varies with system types, system design, cleanroom functions, and the control of critical parameters including temperatures and humidities. In particular, cleanroom cleanliness requirements specified by "cleanliness class" [1],[2] often cast large impact on energy use. A previous study [3] reveals that depending on cleanroom cleanliness classes, annual cleanroom electricity use for cooling and fan energy varies a lot and usually accounts for a large portion of cleanroom energy and operation costs (up to three quarters of the total annual operation costs) in Europe and the US. Another study on a semiconductor cleanroom in Japan[4] found air delivery systems account for over 30% of the total power consumption. It is evident that the main factors dictating cleanroom operation energy include the magnitude of cleanroom airflow rates and how efficiently HVAC systems deliver cleaned and conditioned air to and from cleanrooms.

Improving energy efficiency in cleanrooms may potentially contribute to significant savings in facilities' initial costs as well as operation and maintenance costs. Especially during economy downturns with industry profit margins dwindling, the ratio of cleanroom energy costs to a company's profits naturally increases. In fact, many of the best companies are paying attention to and implementing the latest designs and technologies in energy efficiency. For example, energy consumption by a typical chip manufacturer can be cut 40 percent or more, and the associated greenhouse emissions even more [5]. Whoever best uses energy efficiency to lower costs and increase productivity would gain competitive advantages. This can lead to a higher return of investment if cleanroom owners, designers, and engineers effectively take appropriate energy efficiency measures in their cleanroom facilities. Since it is in the interests of industries to lower cost production to maintain competitiveness, and to maintain or improve profit margins and market shares, it is necessary to reduce capital costs as well as operation and maintenance costs. Implementing energy efficiency in cleanroom systems provides a promising window towards better use of natural resources and energy, which can favorably ameliorate environmental impacts.

Scopes and Objectives

A significant portion of energy use in cleanroom environmental systems is associated with recirculation air systems and often to a lesser degree, the make-up air and exhaust systems. The air systems circulate clean conditioned air through high efficiency particulate air (HEPA) filters for cleanrooms. The recirculation air systems discussed in this paper include three common designs: 1) Fan-tower (FT) with pressurized-plenum; 2) Distributed air handler unit (AHU); and 3) Fan-filter unit (FFU). The airflow performance for environmental systems of ISO Cleanliness Class-5 cleanrooms is reviewed because cleanrooms of this class are among those likely equipped with most energy-intensive environmental systems [3]. Along with discussion of design and operation characteristics and economies of the actual air systems, the paper will examine potential benefits of efficient airflow design that would assist high-technology cleanroom owners, management and engineers to realize cost-savings in their cleanroom facilities.

The objectives of this paper are to 1) review and analyze design factors and operational performance of airflow systems in ISO Cleanliness Class-5 cleanrooms; and 2) demonstrate benefits of efficient cleanroom airflow designs while achieving effective cleanroom contamination control.

Airflow Design for Better Efficiency

A high-performance cleanroom airflow design should achieve two goals: 1) effective contamination control in the cleanroom, and 2) efficient airflow delivery for contamination control in the cleanroom. To maintain effective contamination control for a particular cleanroom, large quantity of cleaned air is often needed by means of recirculation with appropriate addition of make-up air delivery and certain exhaust requirements. How efficiently the conditioned air is delivered for a cleanroom dictates energy needs for operation and may have potential impacts on power systems' availability and reliability.

The following are the major factors determining the air system efficiency: cleanroom activities (e.g., product, process, cleanliness class), airflow rate, airflow distribution, particle size, particle transport rate, spatial pressure control, and system equipment and components. Based upon the analysis of actual cleanroom airflow rates, energy efficiency of actual air handler units (AHUs), and relevant factors affecting airflow performance, this paper summarizes the implications and opportunities for energy efficient airflows.

Cleanroom Airflow Requirements - How much is too much?

It is important for cleanroom designers and operators to understand the roles of air circulation to achieve satisfactory cleanroom performance. Often, the amount of airflow in a given time (i.e., airflow rate in terms of air change rate and/or air velocity), which is part of complex design considerations, becomes the focus of designers and operators when quantifying the air system for effective contamination control. The reality is that there is no simple way to relate a cleanliness class level to a specific cleanroom air velocity or air change rate because of complex factors to be considered in design and operations. It has been common in practice and in ASHRAE and IEST's publications, however, to use cleanroom air velocities and/or air change rates to quantify the amount of airflow requirements.[6], [7]

Fundamentally, there are three major components to characterize cleanroom airflows: 1) the amount of airflow in the cleanroom in a given time, 2) the distribution patterns of airflow (velocities and profile) within the cleanroom, and 3) the spatial pressure impact of airflow in and around the cleanroom. Regardless of air distribution, more air alone may not necessarily be better in terms of the effectiveness of contamination control. To avoid ambiguity, this paper defines cleanroom air velocity as the total circulation airflow rate divided by primary cleanroom floor area (m/s, or fpm); and cleanroom air change rate as the total circulation airflow rate divided by primary cleanroom volume (1/hr). A prior study by Xu et al. [3] reviews relevant publications and has found that there are various ranges of airflow recommended by different entities and publications [6], [7] in the industry, while it was found from in-situ measurements that actually airflow rates (in terms of average cleanroom air velocity and/or air change rate) were often much lower than the recommended ranges. Recent development in updating the IEST Recommended Practice RP-CC-012.1 – "Considerations for Cleanroom Design" [8] proposed that air change rate should be over 200/hr for non-unidirectional airflow for ISO Class-5 cleanrooms, while cleanroom air velocity should be between 0.20 m/s and 0.50 m/s (or 39 fpm and 98 fpm) for unidirectional airflow for ISO Class 5 cleanrooms.

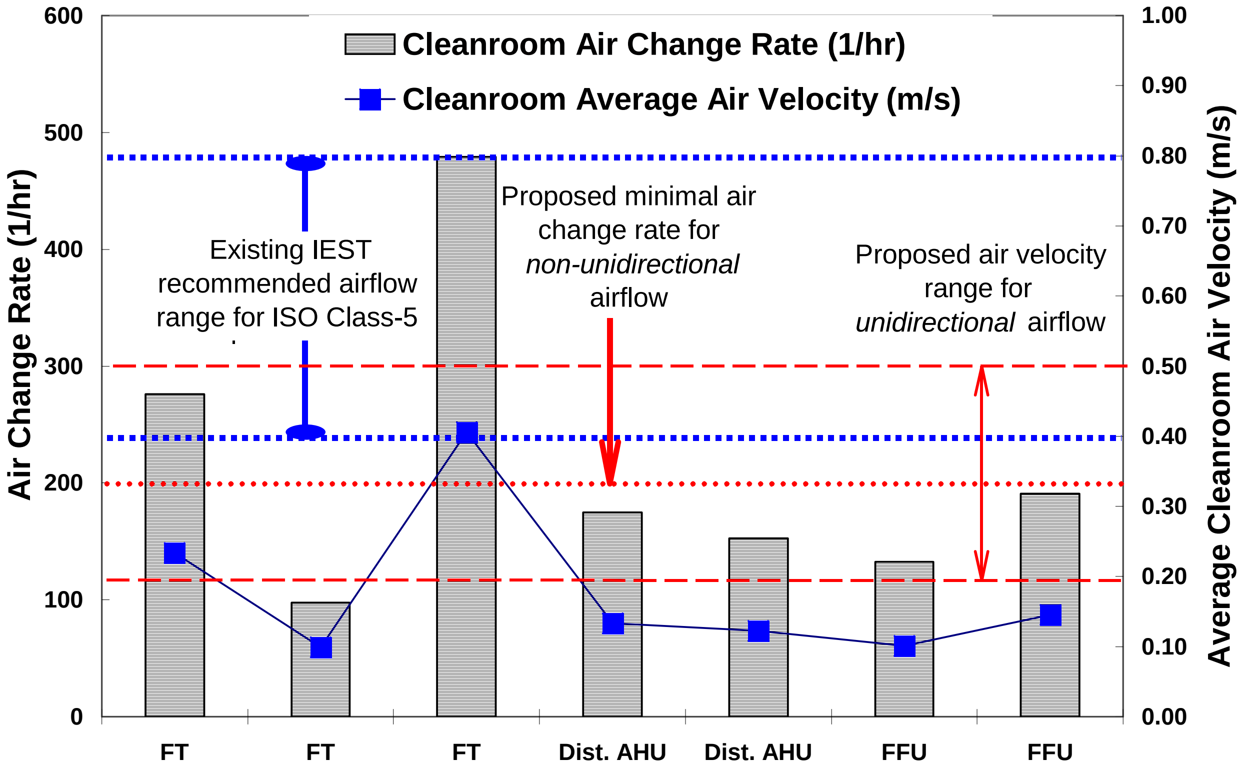

Figure 1. In-situ Class 5 average cleanroom air velocities and air change rates

Figure 1 shows the actual average cleanroom air velocities and air change rates for the ISO Class 5 cleanrooms reviewed in this study, as compare to relevant recommended ranges that have been or are being developed by the IEST. The measured cleanroom air velocities ranged approximately between 0.10 m/s and 0.41 m/s (or 20 fpm and 80 fpm), corresponding to air change rates between 100/hr and 480/hr. This indicates that there was a large variation in air circulation among different systems, depending on design, layout, and cleanroom activities. This also shows that providing good airflow distribution, even airflows with an average cleanroom air velocity of as low as 0.10 m/s can effectively dilute contaminants or transport particles away effectively. The sparkling contrast is that the majority of the actual airflow rates fell far below the commonly recommended ranges (e.g., 0.46 m/s, or 90 fpm in ASHRAE [6]; the lower limit of 240/hr in IEST RP-CC012.1 [7]) and even including the new approved revisions to IEST RP-012.1 (i.e., a lower limit of 200/hr or 0.20 m/s [8]).

Opportunities for a better energy efficiency and savings can very well exist in cleanroom design and control practice. Specifying higher air circulation than is actually needed can result in much larger fan power required and associated initial costs. For example, an additional 10% to 30% airflow supply would increase fan power by approximately 30 to 120%. In addition, the increased fan power used to circulate cleanroom air would also adversely increase additional cooling load due to extra heat generated from fan motor operation. The evidence shown here demonstrated that it is in the interest of cleanroom designers and owners not to overly or blindly specify higher airflow rates than is necessary (or sometimes "recommended") to achieve high performance cleanroom operation.

Energy Efficient Air System Design – Which is more efficient?

Cleanroom air systems usually consist of recirculation air systems, make-up air systems, and sometimes exhaust systems. The types of recirculation systems, their sizes, airflow paths, layout, system components, and other design and control details can largely affect the magnitudes of overall air system efficiency. The bottom line is that reducing resistance in the air path throughout air handler systems can lower pressure drops, and thus require less fan power and energy to recirculate the air needed to maintain effective contamination control. Xu et al. [3] have discovered that energy efficiency of different types of recirculation air systems used to recirculate clean conditioned air for cleanrooms varied dramatically from cleanroom to cleanroom. Fan-tower air systems were generally far more efficient than other types of recirculation air systems (i.e., distributed AHUs and FFUs).

Like those of recirculation air systems, configurations of make-up air systems can have significant impact on overall cleanroom energy consumption. Depending upon local climatic conditions and requirements for cleanroom activities, the treatment of make-up air can be a significant energy user in maintaining the cleanroom's environmental conditions [8]. Make-up air systems, although using much less energy than recirculation systems, are usually much less efficient than their recirculation counterparts.

Cleanroom Spatial Pressures, Filters, and Ceiling Coverage – What is the right choice?

While static pressure in cleanroom air systems have direct impact on the power required to maintain air movement, the control of spatial pressures in a cleanroom relative to its adjacent facilities is critical to an effective contamination control. Depends on actual activities in the cleanroom, accurate pressure control can impact the specific process and act as the barriers (or channel) to the dispersion of contaminants to the unwanted (or intended) areas. For example, a positive cleanroom pressure would be required to keep foreign contaminants from entering the cleanroom; on the other hand, a negative cleanroom pressure would be required to contain contaminants such as bacteria and hazardous materials inside the cleanroom from escaping to outside through leaks in the cleanroom enclosure. The methods of pressure control are related not only to recirculation airflow, but also to the design details of make-up airflow and exhausts.

The air systems recirculate conditioned air through HEPA filters for cleanrooms. On one hand, HEPA filters have different levels of filter efficiencies and effective areas that are less than their actual physical sizes; on the other hand, the ceiling coverage by HEPA filters varies with contamination control requirements. Often, the ceiling coverage by HEPA filters can be anywhere between 25% up to 100%. With lower ceiling coverage, the face velocity of airflow in the filter would tend to be higher given the same airflow, resulting in more fan power demand. Careful considerations should be given when selecting filter efficiency, filters' ceiling coverage, and space layout.

Summary – So what can we learn from here?

The designers and owners of cleanrooms should realize the potential and long lasting energy impact of cleanroom airflow design, and to proactively try to capture benefits via efficient design during planning and design phases. It is important to provide necessary space and appropriate adjacencies for efficient air systems, and to consider applicable types of air delivery systems that use energy efficient components. It is important for designers not to specify excessively higher cleanroom airflow supply than is needed for a specific cleanroom process. The relevant design guidelines or recommendations should be followed only with a grain of salt.

Designers should carefully consider initial costs, operating costs, process loads, and requirements for high cleanroom performance when selecting an energy efficient air system. Integrated approach should be employed to thoroughly evaluate cons and pros of adopting certain design and components. For example, in the case of FFUs, although it is important to carefully consider cleanroom air paths, and to select low air velocities, low pressure cooling coils, designers should realize that FFUs normally have lower static pressures, there would be relatively little pressure left to offset external static pressure after air passes through internal sound attenuators and HEPA filters. For example, the most efficient fan-tower pressurize-plenums may require additional space. It may also require special controls on noises and vibrations, which would not be desired or applicable for certain cleanroom activities. In addition, fan-tower type of systems would normally increase air system static pressures and thus increase the fan power. Therefore, it is necessary to thoroughly compare these undesired consequences against the efficiency gains obtained.

Efficient Airflow Design and Benefits

High-technology manufacturing cleanrooms require high-quality and extremely reliable power. They are among those most likely to seek competitive energy service deals as electricity markets are deregulated. Some of most progressive of high-technology companies have already begun the process and practice of identifying energy efficiency opportunities and service options. Understanding that it costs a lot of money to move air for cleanroom environment, management and owners of cleanroom facilities should pay attention and take necessary measures in optimizing airflow. Unfortunately, there has been tendency in practice to simply jack up air velocities in the anticipation of directly lowering particle counts. There were, however, cases that higher cleanroom air velocities increased the particle counts in the test area, while lower velocities decreased the particle counts at the work areas [10].

Depending on cleanroom cleanliness requirement, cleanroom process, cleanroom size, system design and utility rates, the operation costs may vary significantly. To illustrate the operation cost impact of an air circulation system, Figure 2 shows the fan kWh costs for cleanrooms. Based upon various system energy efficiencies, the figure is based upon an assumed airflow of 1,000,000 m^3/h (or about 583,000 cfm), operating 24 hours a day for the whole year (8,760 hours). According to a projection by Energy Information Administration of US Department of Energy [11], average electricity prices are projected to be somewhere between 6.5 cents per kWh and 6.9 cents per kWh for the next 18 years (till year 2020). Utility rates of these two cases are used to estimate annual fan energy costs (kWh costs), excluding any energy demand charges. The annual fan kWh costs alone for the cleanrooms with less efficient AHUs (i.e., distributed AHUs and FFU) can be anywhere between $150,000 and over $300,000. Significant cost savings opportunities in operating the cleanrooms could be realized by an increase in system efficiency for such air systems.

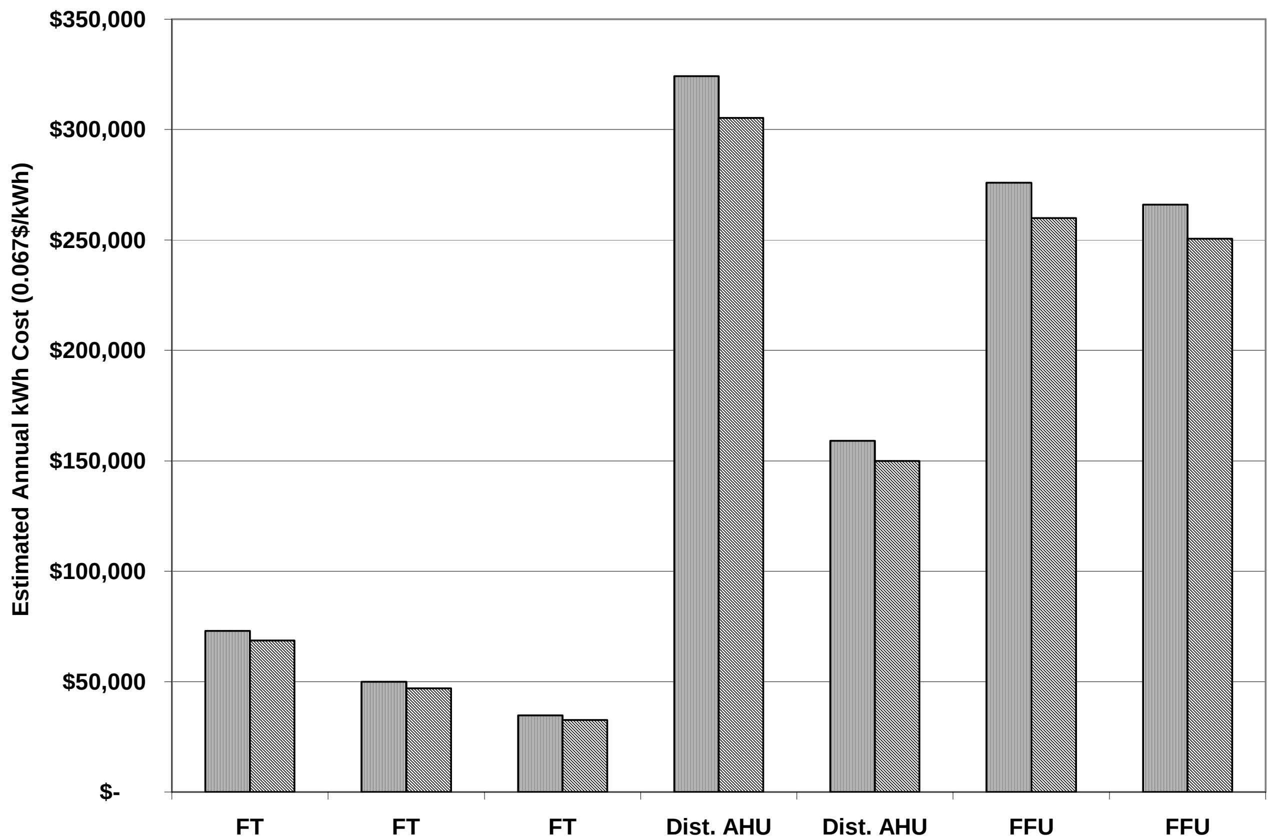

Figure 2. Projection of annual fan kWh cost (fans for air circulation) between year 2002 to 2020 for an 1,000,000 m^3/h (or 583,000 cfm) Class 5 cleanroom

Besides direct cost reductions in cleanroom investment and operation, design for a better energy efficiency can also bring other benefits. These can include 1) improve cost structure such as reducing maintenance cost and increasing power reliability in process and facilities, 2) improve time-to-market in the future cleanroom production, and 3) improve environmental quality and community/industry reputation.

Conclusions and Recommendations

The initial costs of cleanroom air systems and subsequent energy and operation costs are largely impacted by design airflows and loads; therefore, it is very important to evaluate system design parameters using integrated approaches, and to determine appropriate airflow rates. A high performance cleanroom should not only maintain effective contamination control, but also achieve energy-efficient operation of air systems. Based upon the review of in-situ measurements and discussion of an array of design factors, the paper finds that efficient airflow systems in practice would reduce initial costs due to optimized sizing, and help cleanrooms achieve high performance, thus contribute to the business bottom lines in cleanroom industries. The owners and management in cleanroom industries should regard energy efficient design as a strategy in their energy management programs to benefit from cost savings related to energy and operations as well as capital savings, among others. Implementing this approach will also strengthen employee and public perceptions of the company as a quality and environmental leader.

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