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Investigating the Performance of a Minienvironment System

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Biography

Dr. Tengfang Xu is a Program Manager with the Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory (LBNL), Berkeley, California. He obtained his B.Eng and M.Eng degrees from Tsinghua University, Beijing, and a Ph.D. from the University of California, Berkeley. He is a licensed mechanical engineer in California with seventeen-year experience in indoor environment, energy, human factors, and building systems. He serves as a Technical Editor for the *Journal of the IEST*, Illinois.

Abstract

A minienvironment is a localized environment created by an enclosure to isolate a product or process from the surrounding environment. Minienvironments have been gaining popularity to provide effective containment for critical contamination control. The use of minienvironments can provide several orders of magnitude improvement in particle cleanliness levels, while energy intensity may be shifted from the conventional cleanroom systems to the minienvironments that enclose the specific process. The purpose of this paper is to study the energy performance of a minienvironment air system in a ballroom setting, to quantify power density of such a system, and to identify areas for energy savings from high-performance minienvironments.

Introduction

A minienvironment is a localized environment created by an enclosure to isolate a product or process from the surrounding environment [1,2]. Minienvironments, often termed “Separative Devices,” have been gaining popularity to provide effective isolation for critical contamination control. The purpose of using minienvironments is either to protect contamination-sensitive products or processes by isolating them from the ambient environment and workers, or to protect workers or their environment from exposures to hazardous contaminants by isolating the products or processes, or both. Minienvironments can often introduce filtered air through HEPA or ULPA filters at a high airflow speed (e.g., 90-fpm) in order to achieve the desired pressure difference or unidirectional airflows to maintain specific levels of cleanliness and contamination control [3]. Depending on the actual height of minienvironment spaces, air change rates of the supplied air can be much higher than the air change rates of recirculation air in common cleanrooms that are designed to achieve similar cleanliness classification.

Anecdotal industry experience indicates that in some situations, the design and operation of the overall cleanroom might well remain largely unchanged, and that minienvironments (or isolated spaces) are simply adding another set of air movement and air conditioning, requiring more energy to operate. While there are papers and guidelines addressing minienvironments’ design, construction, and operation [4,5,6,7,8,9,10], and yields and production associated with deploying minienvironments, there is nonetheless virtually no data available to quantify the energy efficiency of minienvironment systems [11]. To understand actual energy implications of a minienvironment system, it is necessary to investigate energy performance of a typical minienvironment, and understand its effect on overall cleanroom energy use.

Objectives and Scope

The objectives of this paper are:

1) Develop an understanding of the key parameters contributing to energy performance of a minienvironment

2) Quantify energy performance of the minienvironment air system and identify opportunities for improving its energy performance.

This paper presents the results in the measured energy performance of a selected minienvironment's air system, and compares the energy performance of the minienvironment with that of a cleanroom.

Case Study Methods

The study is designed to measure airflow rates, electric power usage, and air pressures in the minienvironment under various operating conditions. The conditions measured cover the full range of operating points (airflow delivery) that the minienvironment's air system can handle. The key parameters include the following: electric power usage, airflow and air change rate, pressure difference between the space inside the minienvironment and the space surrounding the minienvironment, and energy performance index (EPI).

Electric Power Measurement

The power meter used in this study is a true RMS energy analyzer with an uncertainty of ±3% [12]. The meter records the electric current, voltage, power factor, and actual power supplied to air delivery system for the minienvironment.

Airflow and Pressure Measurement

A VelGrid attached to the electronic micro-manometer [13] measures the average speeds of the airflow delivered out of the face of the fan-filter units (FFUs), which are installed at the ceiling of the minienvironment. The size of individual FFU and HEPA filters is 1 foot by 2 feet. The measurement uncertainty in airflow speeds is ± 3% of reading plus ± 7 fpm from 50 to 2500 fpm. Pressures are measured using a Pitot tube, with a measurement uncertainty of ±2% of reading plus 0.001 inch water column (0.25 Pa) from 0.05 to 50.00 inch water column (or 0.125 to 12500 Pa).

Figure 1 Minienvironment

Results

The minienvironment in this study is a stand-alone open-loop system, with airflow coming through the fan-filter units (FFUs) from the surrounding cleanroom space (Figure 1). The supplied air is filtered through four FFUs, each of which is one by two feet with a depth of two feet. The floor size of the minienvironment is two feet by four feet with an inner space height of seven feet seven inches. The supply air is from the top of the minienvironment and the exhaust opening is in the front toward the bottom. Four identical 1'X 2' parallel FFUs are used in the minienvironment's air system. Each of the FFUs is designed with a single-phase AC motor with adjustable airflow rates or air speeds controlled by a Silicon Controlled Rectifier (SCR) controller. In this study, fan speeds are adjusted manually by adjusting the SCR controller to record the full-range operating conditions that the minienvironment air system can produce. The recorded data include the concurrent power consumption of the minienvironment air delivery system, airflow rate, and pressure difference for each operating condition.

Electric Power and Airflow Rates

Reducing the operating airflow speed not only can reduce FFU fan power, but also may improve cleanliness, lower noise, and improve operating life of the fan. Normally one would expect fan power consumption to increase with an increase in airflow rates. Figure 2 shows that when the airflow speed is under 95 fpm, total electric power supplied to the FFU increases with the increase in airflow rates. In addition, the rate of electric power increase with the airflow rate goes down with airflows when the airflow speed is below 95 fpm (or 760 fpm), at which the total electric power input reaches to a peak. In contrast, when the airflow speed is above 95 fpm, the total electric power decreases with the increase in airflow rate. This indicates that it takes less fan power for the minienvironment's air system to run at a higher airflow rate than it does at a lower airflow rate.

The trends observed in the figure also confirm that with this speed controller, once the initial resistance is overcome, the air delivery becomes easier (and therefore, more efficient) for the system to move the same airflow rate through the air system.

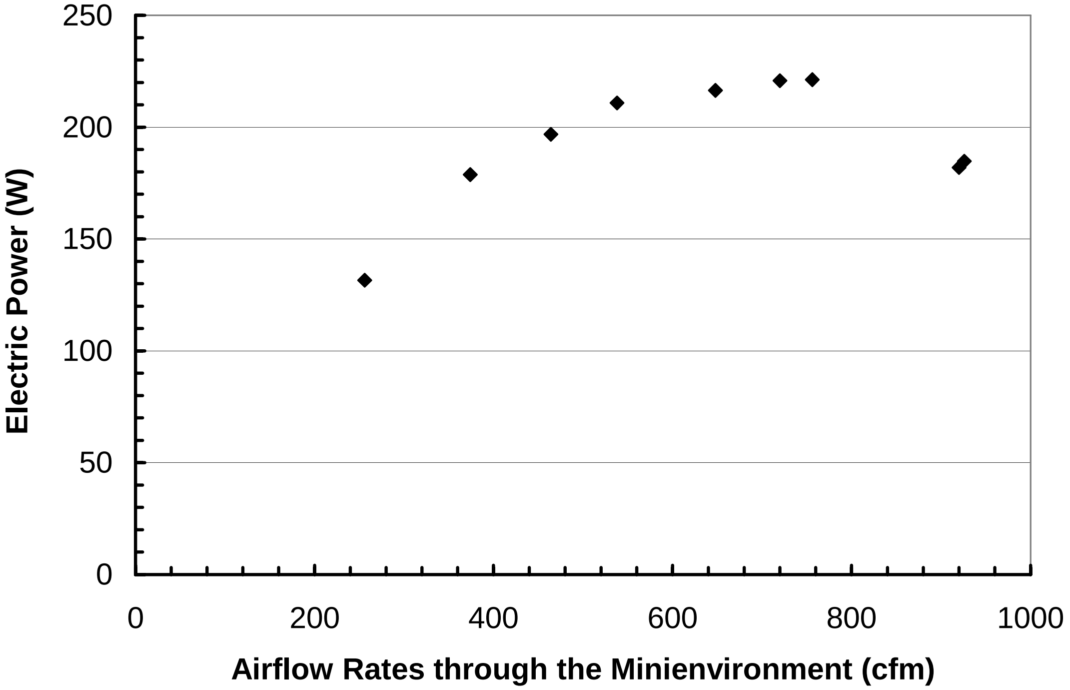

Figure 2 Electric Power and Airflow Rates

Energy Performance Index

In this study, the energy performance index (EPI) of a minienvironment's air system is defined as the total electric power supplied to the fan system divided by the flowrate of the delivered air. A higher EPI means more power is needed for the same airflow rates supplied to and through the minienvironment, corresponding to lower air delivery efficiency in the minienvironment.

Figure 3 shows the results in air system's energy performance index, with the EPI ranging from 0.20 to 0.42 W/cfm corresponding to the range of airflow speeds from approximately 60 fpm to 110 fpm. These airflow speeds correspond to airflow rates in the range of approximately 460 to 900 cfm, and a positive air pressure inside the minienvironment in the range of 0.01 to 0.03 inch water column (or 2.5 Pa to 7.5 Pa). By controlling the airflow, a positive pressure is created to prevent introduction of potential contaminants from the surrounding environment. For common airflow speeds of 50-90 fpm, the measured EPI is within 0.30-0.45 W/cfm.

In general, the EPI values decrease with the delivered airflow rates. The rate of the EPI decreasing is almost constant - indicating an almost linear correlation between EPI and airflow rates. The trend indicates that the air system EPI value becomes lower (more efficient in delivering the air) when the airflow rate through the minienvironment increases.

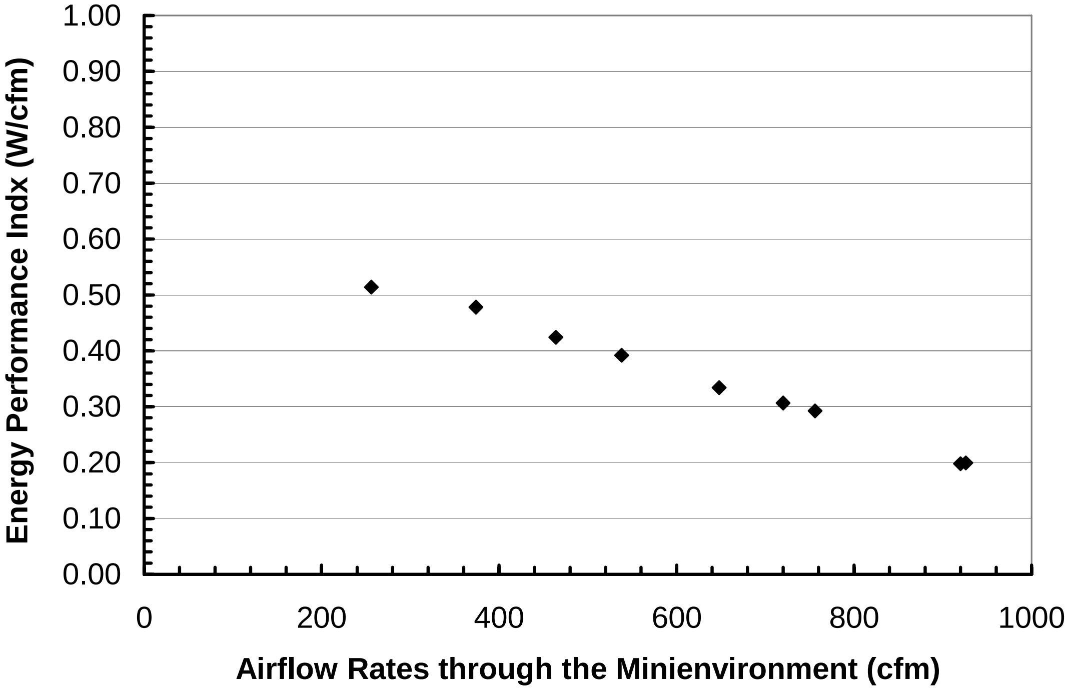

Figure 3 EPI and Airflow Rate

The air system's energy performance index (W/cfm) in this study are in the range of 0.20 W/cfm to 0.45 W/cfm. This is within or lower than the overall benchmarked ranges observed in many large cleanrooms (ISO Class 4 or Class 5) [14]. The recirculation air system efficiency for ISO Class 4 and 5 cleanrooms ranges from approximately 1,100 cfm/kW to 10,500 cfm/kW, corresponding to the approximate range of EPI values of 0.10 to 0.90 W/cfm for all recirculation air systems. Compared to the FFU systems in cleanrooms with ISO Cleanliness Class 5 or lower cleanliness classes, the energy performance index of the minienvironment system appears to be higher, indicating a less energy-efficient air system in the minienvironment. This may suggest opportunities to improve its air systems' delivery efficiency.

Pressure Difference

The air pressure difference is the difference between air pressure in the minienvironment's internal space and that of its ambient surrounding. The purpose of maintaining a positive air pressure in a minienvironment relative to the air in the surrounding spaces is to prevent the less-clean air from being transported to the minienvironment and therefore contaminate the process.

According to IEST CC- RP 028 [1], microelectronic minienvironments spanning between process bay and services chase should be designed to maintain a differential pressure, with a typical process-bay pressure exceeding the service-chase pressure by 0.01 to 0.05 inch water column (or 2.5 to 12.5 Pa). However, this range seems to be experiential and there is no scientific data to specifically support such a range. A rule of thumb is to control the pressure differential with a minimal value of 0.01 inch water column (2.5 Pa) up to 0.03 inch water column (7.5 Pa).

Figure 4 shows that as expected, pressure difference increased with delivered airflow rates, and that the rate of pressure increase is almost constant, indicating an almost linear correlation except for a few points. A higher airflow produced a higher pressure-difference. For example, corresponding to airflow speeds of 50-90 fpm, the pressure difference ranges from 0.008 to 0.02 inch water column (2.0-5.0 Pa); corresponding with airflow speeds of 60-110 fpm, the pressure difference ranges from 0.01 to 0.03 inch water column (2.5-7.5 Pa)

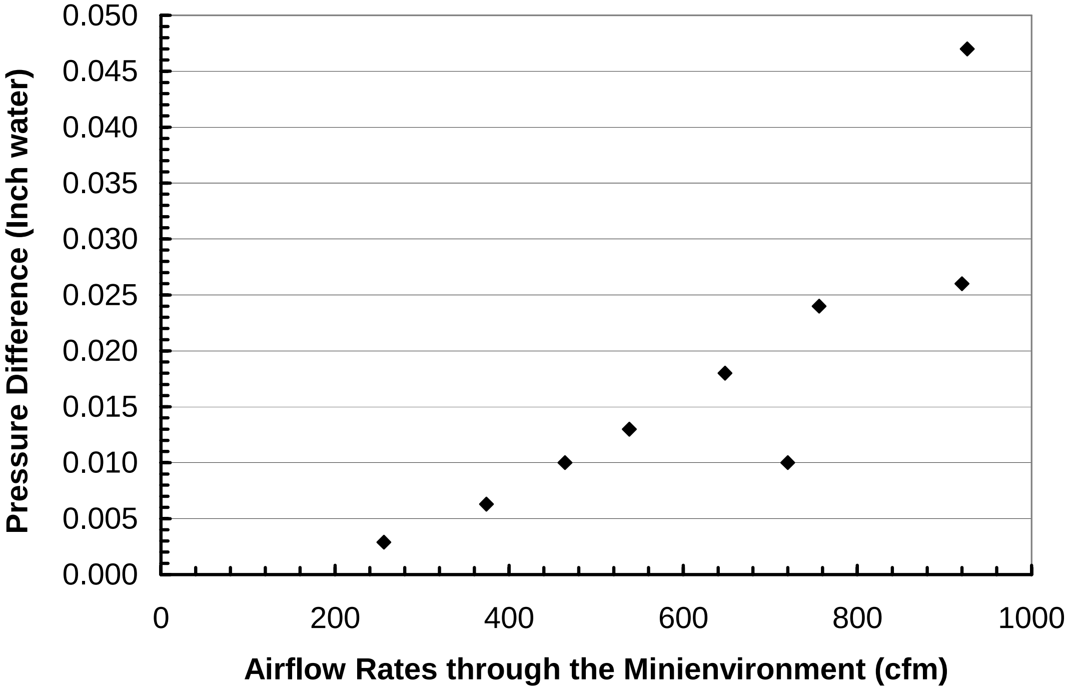

Figure 4 Pressure Difference

Electric Power Density

Figure 5 shows that electric power density changes with airflow speed and pressure differential. Corresponding to the tested operating ranges (30-110 fpm) for this minienvironment, power density ranges from 16.5 W/ft^2 to 23.0 W/ft^2, with a peak of 27.7 W/ ft^2 when the air speed is 95 fpm. This range actually falls within the range of fan power density from previously measured ISO Cleanliness Class 4 cleanrooms is in the range of 16 to 38 W/ft^2 [14]. Given a same airflow speed in general, the FFU power density of the minienvironment tended to be slightly higher than those of cleanrooms of similar cleanliness requirements, especially when the cleanrooms are not fully covered by HEPA filters. Because of the much smaller minienvironment volume compared to that of full-scale cleanrooms (e.g., ballroom), the amount of airflow rate supplied to a minienvironment is significantly reduced. This may suggest opportunities for a significant overall energy savings potential if cleanroom airflows can be lowered due to the vastly smaller volumes of air that must be moved, conditioned, and filtered.

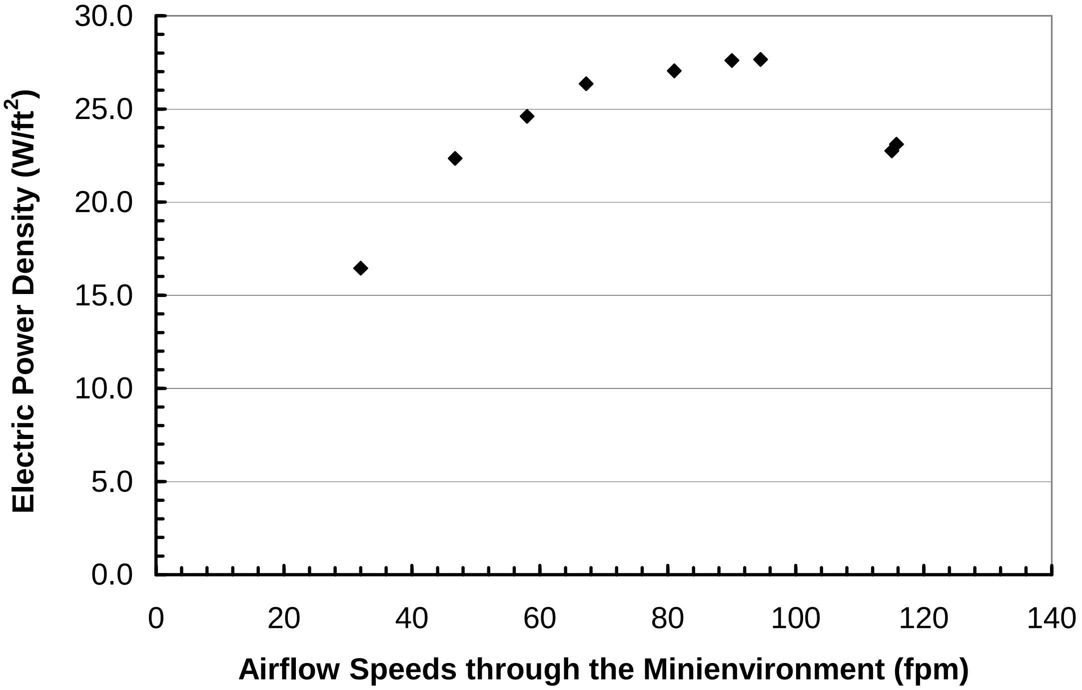

Figure 5 Power Density and Airflow Speeds

Airflows and Air Change Rates

In semiconductor wafer manufacturing, the air supply for a large “ballroom” with cleanliness of ISO Cleanliness Class 4 or ISO Cleanliness Class 5 is filtered and recirculated at rates as high as 500- or 600- air changes per hour, while the wafer manufacturing only takes place in a relatively smaller area within the whole cleanroom space.

In this case study, the minienvironment typically operates with once-through airflow speeds in the range of 60-100 fpm, which is consistent with the airflow speeds commonly observed in conventional large clean spaces. The HEPA/ULPA filter coverage in the minienvironment is 100% while other cleanrooms can have a coverage ranging from 20% up to 100%. If we convert the airflows into actual air change rates for the minienvironment studied, the actual air change rates range from 480 to 800 per hour corresponding to the airflow speeds ranging from 60 fpm to 100 fpm. The air change rate range is higher than the range observed from those of ISO

Cleanliness Class 4 cleanrooms, which are in the range of 385 to 680 per hour corresponding to airflow speeds ranging from approximately 60 fpm to 120 fpm [14].

Conclusions and Recommendations

Minienvironment applications can largely influence the future planning, design, construction, and operation of cleanroom spaces, depending on their specific contamination control requirements. Contamination control for minienvironments can be realized by regulating airflow rates and/or air pressure differentials between minienvironment space and its surrounding space.

This study develops a new performance metric - energy performance index based upon electric power usage per airflow rate to characterize the energy efficiency of airflow systems applicable to minienvironments. A lower energy performance index corresponds to a more energy-efficient airflow delivery system. Providing measured data to quantify energy performance of the minienvironment, this study shows that the energy performance index of a minienvironment for typical operation tends to be in the vicinity of or higher than that of its counterparts in traditional cleanrooms. At the same time electric power density of the air system in such a minienvironment can be higher than that of normal cleanroom systems. This paper also concludes that the energy efficiency of devices used in air systems such as the FFUs and their control mechanism largely affects the overall air delivery efficiency. Based upon the analysis, implementing minienvironments as a means of contamination control may produce overall savings in electric power.

Recommendations from this study include investigating minienvironment energy usage as compared to that of traditional cleanroom systems, integration of minienvironments in cleanrooms, and further analysis of savings potential for future design, construction, operation, and management of cleanroom spaces.

Acknowledgement

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