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Characterization of Minienvironments in a Cleanroom: Assessing Energy Performance and Its Implications

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Characterization of Minienvironments in a Cleanroom: Assessing Energy Performance and Its Implications

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1. Abstract

Filtered fans in cleanrooms can demand up to 400 W or more electric power per square meter of floor area to rapidly supply, re-circulate, and exhaust air. "Minienvironments" that control particle concentrations within enclosures may not only maintain a level of stringent cleanliness, but also offer opportunities in energy savings and reducing operation costs through integration with adjacent cleanrooms. In order to better understand the total performance of minienvironments in operation, this paper characterizes energy performance of five different minienvironments (designated as ISO-Cleanliness-Class-3) that were in operation and were housed in a traditional, larger ISO-Cleanliness-Class-4 cleanroom used in the microelectronic industry. The measured parameters in the field investigation included electric power demand, airflows, in addition to physical characteristics and cleanliness performance of the minienvironments. In this paper, measured energy performance and associated metrics are compared to those of cleanrooms of various cleanliness classes. This paper develops new understanding of energy performance of minienvironments and quantifies the magnitudes of potential energy savings that could result from integrating minienvironments in traditional cleanrooms while achieving effective contamination control. Based upon this study, achieving energy savings by a magnitude of up to 60%-86% was possible in the cleanroom facility housing

the minienvironments. The paper also suggests means of increasing energy-savings in minienvironments applications, including optimal design and operation, and space management in clean spaces.

2. Keywords

Minienvironment, cleanroom, airflow, fan-filter unit, energy, electric power demand, electric power density, cleanliness, contamination control, energy performance index

3. Introduction

Cleanroom air-recirculation systems may account for a significant portion (e.g., 50%) of the HVAC energy use in cleanrooms. In cleanrooms, high electric power density for fans to deliver airflows, defined as the fan’s electric power demand divided by the cleanroom floor area, would normally be expected because of large volume of airflows that is supplied, re-circulated, and exhausted within a given time. Therefore, design of cleanroom airflow systems may have a long-term impact on energy usage [1][2][3] in that the amount of designed airflows significantly affects the operation costs associated with energy, initial equipment costs, and installation costs. In fact, an efficient and optimally sized airflow system may not only reduce initial costs but also help cleanrooms achieve high-performance that benefits effective contamination control, productivity, and reliability.

With the demand for better contamination control in specific applications to achieve higher cleanliness [4][5], e.g., within a localized and relatively small space, it is important to optimize the design of clean spaces, airflows, filtration system to meet cleanliness requirements and to achieve effective particle control. As an added benefit, optimizing airflows, layout, and sizing of clean spaces may potentially offer energy savings.

Expected to maintain a level of stringent cleanliness in a tightened volume of clean spaces, a minienvironment is a localized environment created by an enclosure to isolate a product or process from the surrounding environment [6][7]. The purpose is to achieve effective control of particle concentration in a localized space through maintaining certain airflows and pressure differential [8], and often, supplying unidirectional airflows needed for maintaining cleanliness levels within the space. The advantages in using minienvironments include creating cleanliness class upgrade and process integration, maintaining better contamination control, and potentially reducing energy costs of cleanroom facilities.

The use of energy-intensive fan-filter units (FFUs) in minienvironments may increase the overall energy density of a cleanroom. However, in order to achieve the same cleanliness level within a minienvironment as that of the surrounding cleanroom, the airflow rate supplied to the minienvironment can be significantly lower than the airflow rate supplied to a full-scale cleanroom because of the significantly smaller volume of a minienvironment. This may present potential opportunities for energy savings when the required airflow rates for minienvironments and cleanrooms could be optimized or reduced, concurrently or unilaterally. Therefore, appropriate integration of minienvironments with the surrounding cleanroom may actually help to reduce the overall electric power demand for the cleanroom facility.

Previous investigations in the open literature applied computer simulations or experiments to evaluate cleanliness performance of minienvironments or cleanrooms [9][10][11][12][13][14].

Some studies addressed the impact of production yields by adopting minienvironments [15][16], while ISO and IEST have published the methods or protocols on construction and operation of minienvironments and cleanrooms [4][5][17]. Unfortunately, none of the literature [9-17] sufficiently addressed energy issues associated with minienvironment applications, nor was any quantitative energy data provided.

Whether a minienvironment is configured to actively or passively direct air from the surrounding cleanroom or is built to include independent temperature control, humidity control, and chemical filtration as part of their operation, cleanroom energy use can become more intensive due to the simply added systems [18]. A recent study quantified the electric power density of a minienvironment system as it related to airflows and pressure differential under various operation conditions [19]. Corresponding to operating ranges for the minienvironment studied, electric power density ranged approximately from 183 W/m^2 to 300 W/m^2 (17.0 W/ft^2 to 28.0 W/ft^2) with air speeds from 0.15 m/s to 0.55 m/s (30 fpm to 110 fpm). This range fell within the range of fan power density from previously measured ISO-Cleanliness-Class-4 cleanrooms, i.e., in the range of 172 W/m^2 to 409 W/m^2, or 16.0 W/ft^2 to 38.0 W/ft^2[2]. As a result, the study suggested that energy efficiency opportunities exist through optimizing design and operation of minienvironment air systems such as fan-filter units [19].

Prior to this field characterization, no other published data associated with minienvironments in operation was available to quantify energy performance and energy-savings potential concerning minienvironments in a cleanroom. In order to develop the understanding of energy implications of incorporating minienvironments in cleanrooms, it is necessary to study the magnitudes of electric power demand or energy end-use of various minienvironments as well as those of the surrounding cleanroom, and to evaluate the overall energy implications of cleanrooms adopting minienvironments.

4. Objectives

It is necessary to develop knowledge and field understanding of energy and environmental performance of minienvironments. The specific objective of this paper is to quantify energy performance of minienvironments installed in a semiconductor cleanroom facility in operation, and to evaluate energy saving potential of the cleanroom facility. The technical objectives of this paper include the following:

- Measure and evaluate energy performance of a group of minienvironments as well as the cleanroom housing the minienvironments.
- Compare the energy performance of the minienvironments and that of cleanrooms.
- Evaluate energy-savings potential by applying energy-efficient minienvironments within a cleanroom while achieving effective contamination (particle) control.

5. Approach

Field measurements were carried out to quantify energy performance of minienvironments housed in an ISO-Cleanliness-Class-4 cleanroom. Five typical minienvironments with a cleanliness level designated to be equivalent to or cleaner than ISO-Cleanliness-Class-3 were selected in the study. These stand-alone, self-powered minienvironments were used to provide filtered air through localized HEPA or ULPA filters at certain airflow speeds for various processes or product-testing activities. All of the minienvironments studied maintained a higher level of cleanliness than ISO-Cleanliness-Class-3 that was originally designed.

The measured parameters included electric power demand (representing energy end-use), coupled with concurrent airflow rates, air pressures, and particle concentrations of the minienvironments under normal operating conditions. Energy performance metrics were calculated to characterize the performance of the minienvironments and the cleanroom. For example, air-system efficiency is calculated as airflow rate divided by electric power demand, while electric power density is defined as the electric power demand normalized by floor area of the clean space, i.e., minienvironment, or cleanroom). When appropriate, comparisons are made to evaluate the performance of the five minienvironments with that of the enclosing cleanroom, and other clean spaces (minienvironments and cleanrooms) reported in previous studies [2][19]. Based upon analyses of the measured data, this paper evaluates magnitudes of energy savings that could potentially result from integrating energy-efficient minienvironments with traditional cleanrooms, while maintaining or improving their effectiveness in contamination control.

5.1 Measuring Electric Power Demand

The power meter used in this study was a true RMS energy analyzer with a measurement uncertainty of ±3% [20]. The meter recorded the electric current, voltage, power factor, the actual power supplied to the air delivery systems of the minienvironments in the cleanroom, and the power supplied to the air-handling-unit systems for the cleanroom. The power meter was used with various current transducers (uncertainty ±2%) and voltage transducers to measure the electric current, voltage, power factor, and actual power demand of the air delivery systems. The air delivery systems consisted of FFUs serving the five ISO-Cleanliness-Class-3 minienvironments, and two types of air-handling units serving the ISO-Cleanliness-Class-4 cleanroom. The measured power demand was used to quantify the energy performance of the air systems for the operating minienvironments as well as those of the cleanroom.

5.2 Measuring Airflows, Pressures, and Particle Concentration

In addition to electric power demand measurements, airflow speeds, air pressure differential between the space inside the minienvironments and the space surrounding the minienvironments, particle concentration levels were measured concurrently to provide quantitative data on environmental performance of the minienvironments. Details of the device, measurement uncertainties, and measurement methods were summarized in a separate paper [8].

6. Measured Energy Performance

6.1 The Cleanroom

The ISO-Cleanliness-Class-4 cleanroom housing the minienvironments in this study was equipped with two types of recirculation air systems served the cleanroom: ducted-HEPA-filter and pressurized-plenum. The designed airflows for recirculation were supplied by four air-handling units (176 kW) connected to the ducted-HEPA filters, and three additional air-handling units (121 kW) connected to the pressurized plenum.

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Table 1 shows electric power demand, air-system efficiency, electric power density, and the concurrent airflow rates for the air-recirculation systems, and make-up-air systems in its normal operation.

Table 1 Cleanroom Energy Performance

Air-handling Systems in ISO Class 4 Cleanroom	Units	Recirculation Air (Ducted HEPA Filters)	Recirculation Air (Pressurized Plenum)	Recirculation Air (Combined)	Make-up Air
Airflow Rate	m^3/min	2,700	1,810	4,510	424
	cfm	95,400	64,000	159,400	14,960
Electric Power	kW	24	13	38	11
Airflow Rate per Power Demand	m^3/min/W	0.11	0.14	0.12	0.04
	cfm/kW	3,920	4,870	4,250	1,320
Electric Power Density	W/m^2	115	102	110	33
	W/ft^2	11	9	10	3

Note: Primary cleanroom floor area was 342 m^2. Designed fan power was 297 kW. Designed airflow rate was approximately 9,830 m^3/min, or 347,000 cfm.

The total recirculation airflow rate was approximately 4,510 m^3/min (159,400 cfm), equivalent to about 46% of designed airflow rate of 9,830 m^3/min, or 347,000 cfm. This corresponded to the fan power of 38 kW, which was approximately 13% of the designed fan power (297 kW) for recirculation air. The average of measured recirculation-fan power density for the cleanroom was approximately 110 W/m^2 (10.0 W/ft^2), which was lower than the originally designed 872 W/m^2 (81.0 W/ft^2). Apparently, the fan motors were oversized and therefore the air recirculation probably induced a much lower pressure drop within the systems than designed. The overall recirculation airflow rate per fan power demand was 0.12 m^3/min/W (4,250 cfm/kW), which was about three times higher than the designed efficiency of 0.03 m^3/min/W (1,170 cfm/kW).

6.2 Minienvironments

For the selected minienvironments within the cleanroom, recirculation air was supplied through FFUs to the minienvironments. The operating efficiency of FFUs and the whole air systems in the minienvironments can vary considerably pending various operating conditions. In this study, air-system efficiency was calculated as airflow rates divided by the fan power demand of the air systems of concerns. Table 2 shows field measurement results including airflow rate, electric power demand, air-system efficiency, energy performance index, and electric power density for the five minienvironments studied.

Table 2 Minienvironment airflow and electric power demand

Minienvironments	Units	A	B	C	D	E	A-E Sum	Average
Airflow Rate	m^3/min	141	21	26	22	106	317	-
	cfm	4,990	750	930	790	3,730	11,190	-
Electric Power	kW	2.1	0.4	0.4	0.3	1.1	4.3	-
Airflow Rate per Power Demand	m^3/min/W	0.07	0.06	0.06	0.09	0.09	-	0.07
	cfm/kW	2,350	1,960	2,250	3,110	3,270	-	2,600
Energy Performance Index	W/(m^3/min)	15.0	18.0	15.7	11.4	10.8	-	14.2
	W/cfm	0.43	0.51	0.44	0.32	0.31	-	0.40
Electric Power Density	W/m^2	335	320	246	343	277	-	304
	W/ft^2	31	30	23	32	26	-	28

Note: Airflow rate numbers (cfm) and air-system efficiency (cfm/kW) were rounded-ups.

6.2.1 Energy Performance Index (EPI)

The energy performance index (EPI) of a minienvironment's air system is defined as the total electric power supplied to the minienvironment's fan system divided by the airflow rate in the minienvironment [19]. A higher EPI value under the same operating condition means that more electric power is demanded for supplying the same airflow rate to the minienvironment, thus corresponding to lower energy-efficiency of an air-delivery system in the minienvironment.

Figure 1 shows measured EPI values of five minienvironment systems compared to that of the surrounding cleanroom (ISO-Cleanliness-Class 4). The EPI values of the five minienvironments (designed as ISO-Cleanliness-Class 3) showed a wide range, i.e., ranging from 10.8 W per m^3/min to 18.0 W per m^3/min (0.31 W/cfm to 0.51 W/cfm), corresponding to airflow speeds ranging from approximately 0.27 m/s to 0.50 m/s (or 52 fpm to 99 fpm). In addition, the EPI values of the ISO-Cleanliness-Class-3 minienvironments were consistently higher than that of the surrounding ISO-Cleanliness-Class-4 cleanroom (0.24 W/cfm, or 8.5 W per m^3/min) corresponding with a lower airflow speed.

As the trend line in Figure 1 shows, EPI values among these minienvironments tended to decrease with the increase in airflow speeds (or airflow rates normalized by minienvironment floor area) inside the minienvironments. This trend indicates that within the measured operating range, lower EPI values (more efficient in delivering the air) tended to correlate with higher airflow speeds for the minienvironments. This trend was similar to the finding from a previous study on a typical stand-alone, open-looped minienvironment system, which exhibited an operating range from 0.30 m/s to 0.50 m/s (or 60 fpm to 100 fpm) in the minienvironment [19]. However, EPI values of the minienvironments in this study were slightly higher when compared with that of the other minienvironment operating with the similar airflow speeds.

Figure 1 also includes measured EPI values for the various ISO-Cleanliness-Class-4 cleanrooms that were previously studied [2], which ranged between 7.4 to 18.7 W per m^3/min (0.21 W/cfm to

0.53 W/cfm). The EPI values for the minienvironments, which generally operated at a similar or lower airflow speed, were generally higher than those of the cleanrooms studied.

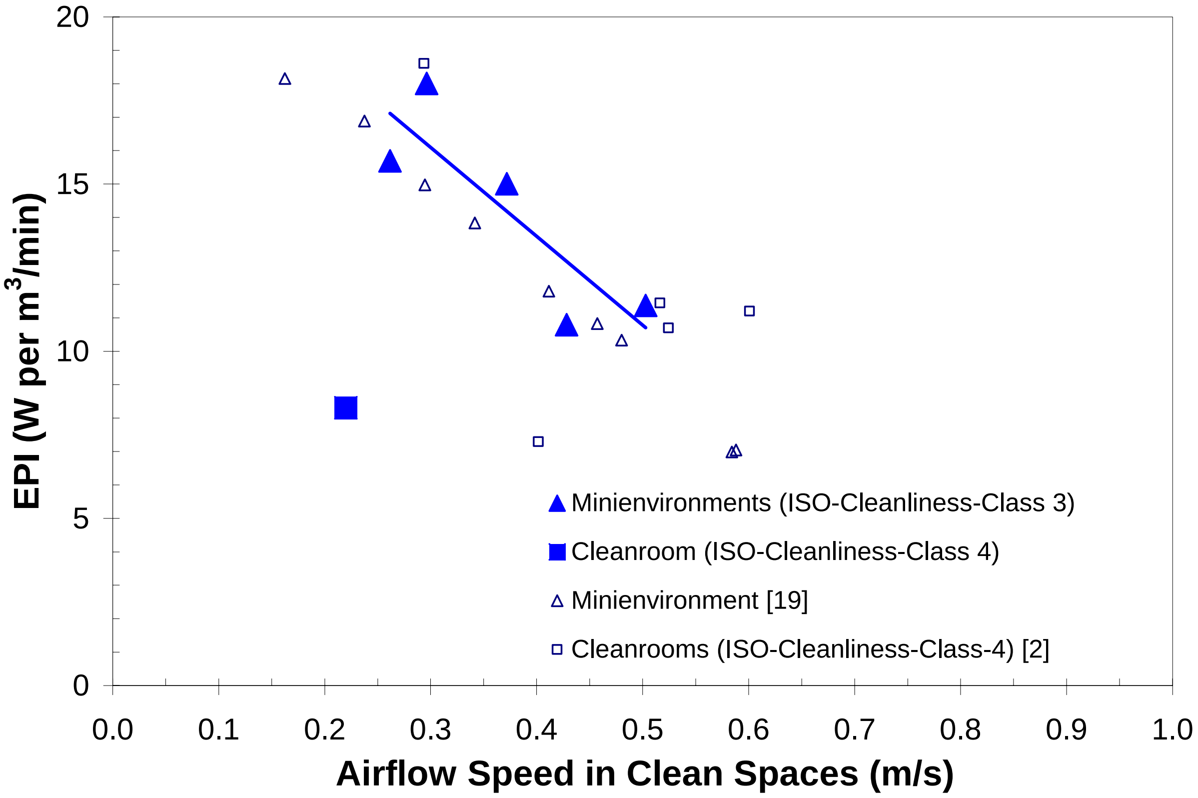

Figure 1 Comparing energy performance indices of minienvironments and cleanrooms

6.2.2 Electric Power Density

Electric power density is in fact the electric power demand required for supplying airflow to the clean space such as a minienvironment or a cleanroom normalized by the floor area of the primary clean space intended for contamination control, i.e., floor area of an individual minienvironment or the primary floor area of a cleanroom.

Figure 2 shows the electric power density of the air systems for the five ISO-Cleanliness-Class-3 minienvironments with a trend line included, and that of the air-recirculation fans serving the ISO-Cleanliness-Class-4 cleanroom in this study.

The air-recirculation systems of the ISO-Cleanliness-Class-4 cleanroom in this study included pressurized-plenum and ducted-HEPA recirculation air systems. They collectively exhibited a much lower level of electric fan-power density than those of the minienvironments. Specifically, electric power density of air-supply systems in the five minienvironments ranged from 280 W/m^2 to 344 W/m^2 (26.0 W/ft^2 to 32.0 W/ft^2) with an average of 304 W/m^2 (28.3 W/ft^2), while the electric power density of the air-recirculation fans for the ISO-Cleanliness-Class-4 cleanroom was 110 W/m^2 (10.2 W/ft^2). The higher electric power density of the minienvironments corresponded to the airflow speeds ranging from approximately 0.27 m/s to 0.50 m/s (or 52 fpm to 99 fpm), while the lower electric power density of the cleanroom corresponded to an average airflow speed of 0.22 m/s (43 fpm) in the cleanroom. A combination of the following reasons probably contributed to the higher power density in the minienvironments:

- The average airflow speeds in the minienvironments were higher than the average air speed in the surrounding cleanroom.

- The stand-alone minienvironment air systems (fan-filter unit systems) with smaller fans were less energy-efficient in delivering air to the intended space, compared to the air-recirculation systems consisting of pressurized-plenum or ducted-HEPA systems typically with larger fans serving the cleanroom.

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- The ceiling of all minienvironments was fully covered by the HEPA filters while the ceiling of the enclosed cleanroom was not fully covered by HEPA filters.

As the trend line in Figure 2 shows, electric-power-density values of the minienvironments tended to increase with the increase in delivered airflow speeds (or airflow rates divided by the minienvironment floor area) inside the minienvironments. This trend indicates that within the measured operating range, higher values of electric-power-density for the minienvironments (more energy intensive in delivering the air) correlated to higher airflow speeds in the minienvironments. This trend was similar to the finding from a previous study on a minienvironment [19] within a certain airflow range (i.e., up to 0.50 m/s).

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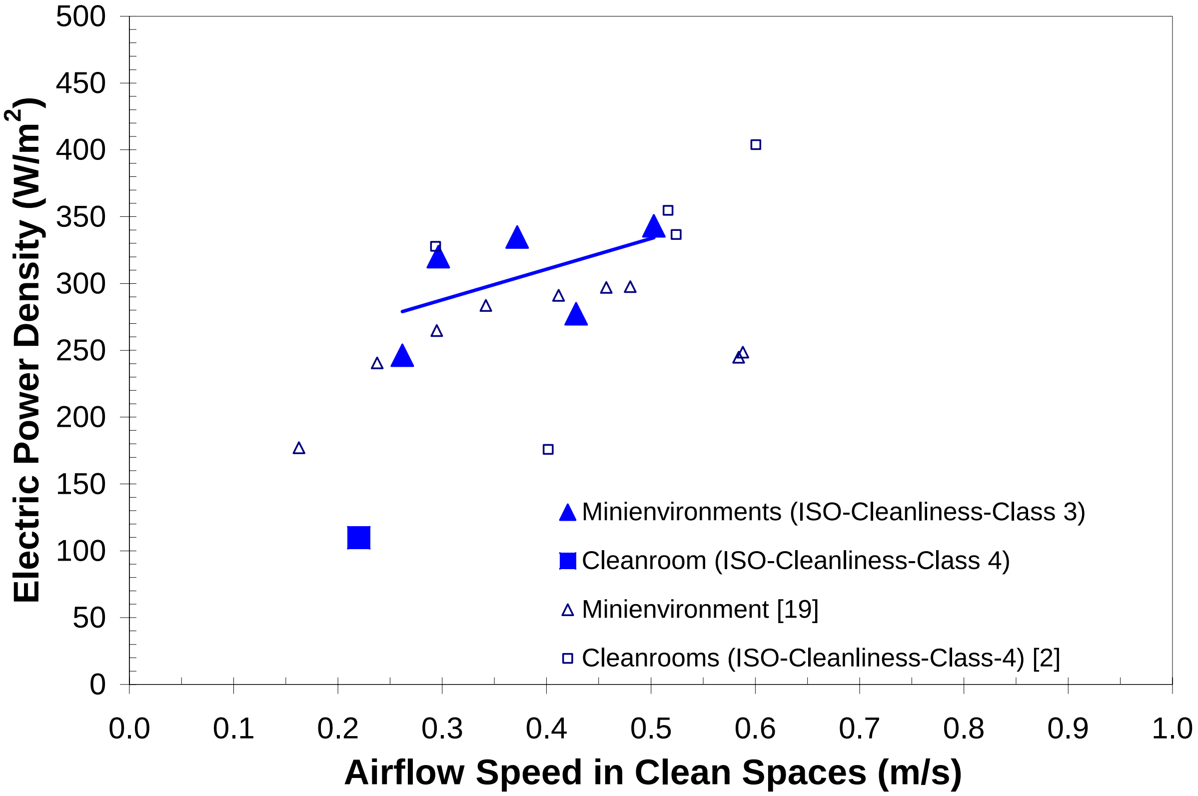

Figure 2. Comparing Electric Power Density of Minienvironments and Cleanrooms

Figure 2 includes the electric power density of the air systems reported in a previous study [2]. While the air-recirculation systems of the ISO-Cleanliness-Class-4 cleanroom in this study collectively exhibited a much lower level of electric fan-power density than those of the minienvironments, they appeared to have lower fan-power density when compared with the group of ISO-Cleanliness-Class-4 cleanrooms with a range of approximately 172 W/m^2 to 409 W/m^2 (16.0 W/ft^2 to 38.0 W/ft^2) reported in a previous study [2]. Those cleanrooms were operating at airflow speeds ranging from 0.40 m/s to 0.60/m/s (or 80 fpm to 120 fpm), higher than the average speed of 0.22 m/s (or 43 fpm) for the ISO-Cleanliness-Class-4 cleanroom in the current study.

In addition, electric-power-density values of most minienvironments in this study were slightly higher when compared with that of the other minienvironment under the similar range of airflow speeds [19]. Given that electric power density of FFU device typically ranged from 215 W/m^2 to 355 W/m^2 (20.0 W/ft^2 to 33.0 W/ft^2) or higher at the airflow speeds in the vicinity of 0.25 m/s (50 fpm) [21][22], the minienvironments in this study exhibited similar power density levels of some of the fan-filter units.

In summary, the actual performance data suggests that 1) within the range of airflow speeds measured from the five minienvironments (0.27 m/s to 0.50 m/s, or 52 fpm to 99 fpm), the electric power density of minienvironments typically increased with the increase of average airflow speeds; and 2) the electric power density of the five minienvironments were higher than that of the cleanroom. Given that the airflow speeds were found to be higher than the adjacent cleanroom, and that the minienvironments actually maintained the cleanliness levels much better than originally designed, i.e., ISO-Cleanliness-Class-3 [8], there could be opportunities of reducing airflows and/or improve energy efficiency of the FFUs installed in the minienvironments while retaining effective particle control.

7. Analysis and Discussion

Based upon the measurements in this case study, the average of electric power density of the selected sample ISO-Cleanliness-Class-3 minienvironments was 304 W/m^2 (or 28.3 W/ft^2), while the electric power density for air-recirculation systems in the surrounding ISO-Cleanliness-Class-4 cleanroom was 110 W/m^2 (or 10.2 W/ft^2). As a result, the overall electric power density of the air-recirculation systems for the stand-alone open-looped minienvironments and the ISO-Cleanliness-Class-4 cleanroom as a whole was therefore estimated to be approximately 145 W/m^2 (or 13.4 W/ft^2).

The following includes two approaches to assess magnitudes of energy savings by implementing energy efficient minienvironments and integration them with a surrounding cleanroom of various grades of cleanroom cleanliness. The first approach, termed "case-based," is based upon the measurements from the study, while the second approach, termed "design-based," is based upon assumptions for various design scenarios coupled with field findings.

7.1 Case-based Analysis of Energy Saving Potential

The measured overall electric power density of 145 W/m^2 (or13.4 W/ft^2) for the minienvironments and the cleanroom as a whole is used as the base case for performance comparison. This indicates that there could be opportunities in optimizing the efficiency of the FFUs in the minienvironments,

First, improving the energy efficiency of the minienvironments would create energy-saving opportunities for the overall cleanroom facility. For example, assuming that 40-50% reduction in the minienvironments' power demand would be possible through optimizing airflow speeds in addition to improving the unit's efficiency, total electric power savings would be approximately 10-12% compared to the base case, as is illustrated Table 3. Second, if the electric power density of the fans for cleanroom recirculation air could be reduced by one-third, the overall power savings resulting from implementing the minienvironments and reduced fan power would be 25%.

Table 3 Case-Based Analysis of Energy-savings

Case Study Based	Floor Area (ft^2) / (m^2)	Total Electric Power (kW)	Electric Power Density (W/ft^2)/(W/m^2)	Estimated Energy-savings
ISO-Cleanliness-Class-3 Minienvironment	424/39	12.0	28.3/304	-
ISO-Cleanliness-Class-4 Cleanroom	3680/342	37.5	10.2/110	-
ISO-Cleanliness-Class-4 Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	49.5	13.4/145	Base case
ISO-Cleanliness-Class-4 Cleanroom and Improved ISO-Cleanliness-Class-3 Minienvironment (by 50%)	3680/342	43.5	11.8/127	12%
Improved ISO-Cleanliness-Class-4 Cleanroom (by 33%) and ISO-Cleanliness-Class-3 Minienvironment	3680/342	37.0	10.1/108	25%
Non-Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	12.0	5.3/57	61%

In another scenario, if the minienvironments were to operate within a non-cleanroom space, meaning that the surrounding cleanliness level (ISO-Cleanliness-Class 4) was not implemented, the overall power savings resulting from implementing the minienvironments and reduced fan power (e.g., office environment) would be approximately 61%. This illustrates that significant energy savings can be achieved by eliminating surrounding cleanliness requirement (i.e., the requirement for ISO-Cleanliness-Class-4 cleanroom cleanliness being relinquished) while assuming that the effective contamination control in ISO-Cleanliness-Class-3 minienvironments could be achieved. The challenge, however, lies in whether or not it is feasible to undergo such change. For example, such a change could be that all processes were to be carried out in minienvironments, which at the same time effective contamination control was to be achieved.

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7.2 Design-based Analysis of Energy Saving Potential

Previous studies indicated that the fan-power density of air recirculation systems in cleanrooms tended to go up with tighter requirements for ISO Cleanliness Class [2]. For example, the fan-power densities of a group of ISO-Cleanliness-Class-4 cleanrooms ranged from 172 W/m^2 to 409 W/m^2 (16.0 W/ft^2 to 38.0 W/ft^2), with an average of approximate 320 W/m^2 (30.0 W/ft^2). This range was generally higher than that of the group of ISO-Cleanliness-Class-5 cleanrooms, which equaled to 142 W/m^2 (13.2 W/ft^2) [2].

The fan-power densities of cleanrooms and minienvironments are listed in Table 4. Because there was no measured data of the fan power density for an ISO-Cleanliness-Class-3 cleanroom, a simplified assumption is taken here, i.e., an ISO-Cleanliness-Class-3 cleanroom was designed to have a fan-power density of 409 W/m^2 (38.0 W/ft^2), which was the upper range of the ISO-Cleanliness-Class-4 cleanrooms previously studied.

Table 4 Design-Based Analysis of Energy-savings

Design based	Floor Area (ft^2) / (m^2)	Total Electric Power (kW)	Electric Power Density (W/ft^2) / (W/m^2)	Estimated Energy-savings
ISO-Cleanliness-Class-3 Minienvironment @12% occupancy	424/39	12.0	28.3/304	-
ISO-Cleanliness-Class-3 Cleanroom	3680/342	139.8	38.0/409	Base case
ISO-Cleanliness-Class-4 Cleanroom	3680/342	109.3	29.7/320	-
ISO-Cleanliness-Class-5 Cleanroom	3680/342	48.6	13.2/142	-
ISO-Cleanliness-Class-4 Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	121.3	33.0/355	13%
ISO-Cleanliness-Class-5 Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	60.6	16.5/177	57%
Non-Cleanroom and ISO-Cleanliness-Class-3 Minienvironment	3680/342	19.3	5.3/57	86%

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Assuming an ISO-Cleanliness-Class-3 cleanroom is designed with no additional ISO-Cleanliness-Class-3 minienvironment in the facility, we may use this as the base case to estimate energy savings from various designs that would implement minienvironments. For example, we may estimate the energy savings from implementing ISO-Cleanliness-Class-3 minienvironments in such a cleanroom while making the surrounding cleanroom less stringent in terms of its ISO Cleanliness Class (e.g., from Class 3 to Class 4, Class 5, or non-cleanroom, respectively).

If the minienvironments occupy 12% of the total cleanroom floor while they were to operate within an ISO-Cleanliness-Class 4 cleanroom, the overall power savings resulted from implementing the minienvironments and the change in cleanliness requirement would be approximately 13%. Similarly, if they were to operate within an ISO-Cleanliness-Class 5 cleanroom, the overall power savings due to the minienvironment implementation would be approximately 57%. Furthermore, if they were to operate within a non-cleanroom space, meaning that the surrounding cleanliness level is not implemented, the overall power savings from implementing the minienvironments and largely reduced fan power (e.g., office environment) would be approximately 86%. This illustrates that lowering or eliminating cleanliness requirements for the adjacent cleanroom (i.e., the requirement for ISO-Cleanliness-Class-3 cleanliness being relinquished) while maintaining effective contamination control in the designated minienvironments could result in significant energy savings.

In this paper, electric power density of air-recirculation systems in the ISO-Cleanliness-Class-4 cleanroom was measured as 110 W/m^2 (or 10.0 W/ft^2), within which a number of minienvironments were located. The measured electric power density of the air-recirculation systems was much lower compared to the group of ISO-Cleanliness-Class-4 cleanrooms with a range of 172 W/m^2 to 409 W/m^2 (16.0 W/ft^2 to 38.0 W/ft^2) in a previous study [2]. This suggests that electric power savings from adopting the same ISO-Cleanliness-Class-3 minienvironments and reducing the power density of air recirculation systems in the surrounding cleanroom may become even greater.

7.3 Discussion

As analyzed, reducing the electric power density of the cleanroom, implementing energy-efficient minienvironments, and optimizing facility design can collectively contribute to energy savings while operating clean spaces. For example, reducing the fan power density through optimizing floor area of the minienvironments and cleanrooms may lead to overall energy savings. Because of the much smaller minienvironment volume compared to that of full-scale cleanrooms (e.g., ballroom), the amount of airflow supplied to the minienvironments for any given time could be significantly reduced. This may present potential opportunities for significant overall energy savings because of the vastly smaller volumes of airflow that must be moved, conditioned, and filtered within a given time.

In general, in order to create opportunities for significant overall energy savings, measures should be taken to reduce fan power for both minienvironments and cleanrooms. The measures may include: 1) reducing electric power demand and density of the minienvironments through optimizing design, operation, and integration, e.g., reduce the airflow and pressurization inside the minienvironments, selecting energy efficient fan-filter units for active minienvironments; and

2) reducing electric power demand and density of the primary cleanroom housing the minienvironments.

8. Conclusions

This paper quantified energy performance of five different minienvironments designated as ISO-Cleanliness-Class-3 that were housed in a traditional, larger ISO-Cleanliness-Class-4 cleanroom used in the microelectronic industry. This study evaluated magnitudes of energy-saving potential of the various design, operation, and management of clean spaces when minienvironments are integrated with a traditional, large cleanroom. For example, based upon the field data and further analysis, achieving energy savings in the cleanroom fan systems by a magnitude ranging from as low as 10%, or as high as up to 60%-86% was possible. While minienvironments selected in this study were effective in maintaining particle-concentration levels within what was originally designed, energy efficiency levels of the minienvironments in this study were found to vary significantly, and were collectively lower when compared with their cleanroom counterparts. At the same time, electric power density of the minienvironments appeared to be higher than that of cleanrooms with a lower ISO cleanliness grade. In addition, reducing power density of air systems, and optimizing the required airflow rates for minienvironments and the surrounding cleanroom may result in significant energy savings while maintaining effective particulate filtration control.

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