Toward Green Systems for Cleanrooms: Energy Efficient Fan-filter Units

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Abstract

The paper presents results of laboratory-measured performance of fan-filter units (FFUs) used for cleanrooms. A total of twenty FFUs collected from the market were tested, including thirteen 1220 mm x 610 mm (or 4 ft x 2 ft) units and seven 1220 mm x 1220 mm (or 4 ft x 4 ft) units. The paper concludes that there are wide variations in FFUs' energy performance, and that there are opportunities in improving energy efficiency and lowering operating costs of FFUs. Furthermore, the paper suggests the benefits of having a uniform method for testing and reporting FFU performance. Such a testing method and recommended practice guideline is under development, with heavy input from FFU suppliers, users, and independent institutions that include Lawrence Berkeley National Laboratory (LBNL), Industrial Technology Research Institute (ITRI), and Institute of Environmental Sciences and Technology (IEST). An integrated approach with the participation from designers, suppliers, users, and utility companies can help to identify energy-efficient FFUs that are required for many cleanroom applications.

Keywords

Cleanroom, fan-filter unit (FFU), energy efficiency, green system, electric power use, energy performance index, operating cost

Introduction

There are challenges and benefits in green designs that integrate technology with architecture and natural resources. Cleanroom HVAC systems account for a large portion of energy use in cleanrooms. Improving energy efficiency of HVAC systems and their components can contribute to high-performance of cleanrooms. Recent studies have found that the performance of HVAC systems varies significantly from cleanroom to cleanroom largely because of various factors, such as contamination control requirements, air handling unit designs, air system resistance, and efficiency levels offered by system components [1], [2]. The studies also uncovered energy-saving opportunities in many cleanroom applications. In fact, optimizing aerodynamic performance in air recirculation systems appears to be a useful approach to improve energy efficiency in cleanrooms.

A fan-filter unit (FFU) usually consists of a small fan, a controller, and a HEPA or ULPA filter enclosed in a box, which fits into common cleanroom ceiling grids (e.g., 4 ft x 2 ft or 4 ft x 4 ft). The fans force air through the filters and through the entire cleanroom. The large number of small fans can consume considerable energy in providing air recirculation. In recent years, fan-filter units are being used more and more in air recirculation systems in industrial cleanrooms. As a matter of fact, their ease of installation and adaptability to various production configurations and control schemes has met specific facility requirements and earned wide-scale deployment. Where FFU applications are required, having comparable information on FFU energy performance would enable selection of more efficient units to improve energy efficiency, while maintaining and improving contamination control.

Typical manufacturer's data sheets usually contain claims that are seemingly similar; however, they do not reveal test methods, if at all exist. Furthermore, statements of performance data that include power, airflow, and sound are commonly vague and could be misleading. In practice to date, there is no published testing method that FFU suppliers and users could consistently adopt when providing or reviewing performance information. As a result, suppliers' performance data cannot be meaningfully compared and its usefulness is minimal. To provide data for both users' and manufacturers' reference, ITRI has conducted relevant measurements to provide airflow, energy, sound, and vibration performance data for FFUs on the market since 1999[3]. Part of the data was released in 2001, along with a brief description of the test procedure that is consistent with industry standards for testing fan systems [4], [5].

This paper briefly describes the laboratory test methods developed by LBNL [6], with a focus of FFU energy and aerodynamic performance. The laboratory test results in this paper are based upon twenty FFUs that entered the market since 2001. These FFUs were obtained by ITRI and tested at ITRI's laboratory facility.

Purposes

The purposes of this paper are (1) present laboratory-testing results on aerodynamic and energy performance of twenty FFUs (2) compare unit performance of these sample FFUs; (3) discuss benefits of the testing standard, and its further integration into the IEST Recommended Practice (RP) guideline for FFU performance testing.

This paper does not include other performance metrics such as sound, vibration, filtration efficiency, outlet flow uniformity, or in-situ performance. These are nonetheless important to overall FFU performance; and some of these are covered in relevant standards, certification documents, or recommended practices [7], [8], [9].

Approaches

The paper evaluates the laboratory measurement results from twenty sample FFUs including thirteen 4 ft x 2 ft and seven 4 ft x 4 ft models. These were tested from 2001 to 2004 at ITRI's facility. The FFUs were connected with an inlet chamber setup that is consistent with other standard test methods to determine a fan's aerodynamic performance [4]. The chamber contains a multiple-nozzle bank for recording airflow rates through the tested unit. The airflow from the immediate downstream of the FFUs was discharged to the open space. A booster fan and a damper were installed at the chamber inlet to modulate air pressures inside the chamber so that the airflow across the FFUs was also controlled. Figure1 illustrates the basic measurement layout. Details of the test method are described in [6] and [10].

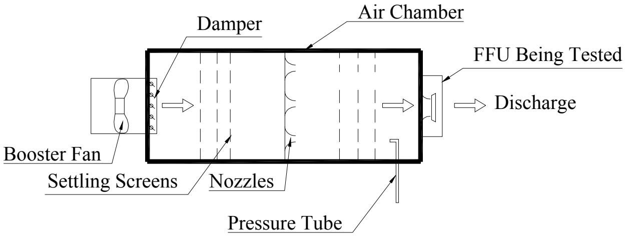

Figure 1. Laboratory measurement layout

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Laboratory Measurements and Metrics

To understand the performance of each FFU unit, relevant metrics were developed to evaluate energy and aerodynamic performance. Data analysis was then performed to quantify metrics at various conditions, and median values of energy performance were identified. The following defines key metrics used in this paper:

- Total Pressure Efficiency: Ratio of airflow velocity power to electric power input to an FFU
- Energy Performance Index (EPI): Unit's total power usage normalized by the airflow rate through the FFU under certain conditions

The uncertainty in the airflow and pressure measurements is within ±2.5%. A power meter measured actual power input of an FFU with the measurement uncertainty within ±0.5%. Velocity pressures of airflows with speeds of 0.50 m/s or lower would only account for an insignificant fraction (<0.5%) of the total pressures [10]; therefore, values of static pressure rise or total pressure rise are expressed interchangeably in this paper.

Outcomes

1. Airflow Rates, Pressure, and Total Pressure Efficiency

Figure 2 shows the curves of FFU pressure rise vs. airflow speed at FFU exit. Common cleanroom applications require an FFU exit velocity in the range of 0.3 to 0.45 m/s. Most of the FFUs exhibited a pressure between 100 Pa to 200Pa within that velocity range, representing common system pressures in modern day cleanrooms. On the other hand, for a typical cleanroom system resistance of 100 Pa (or about 0.4 inch water), most of the FFUs would operate at airflow speeds typically ranging from 0.30 to 0.50 m/s (or about 60 to 100 fpm). The FFU total pressure efficiency includes electrical efficiency and mechanical efficiency of the whole FFU unit and it takes into account fan motors, transformers, etc. The expression can be written as

$$E_t = P_t Q / W \qquad (1)$$

where

P_t is the FFU total pressure rise (Pa)

Q the airflow rate (m^3/s), and

W is the total electric power input to FFU (W).

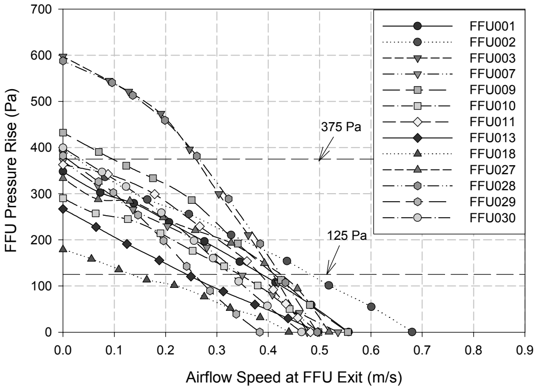

Figure 2. 4'x2' FFU pressure rise vs. airflow speed at FFU exit

Figure 3 shows performance curves of individual 4 ft x 2 ft FFUs in terms of their total pressure efficiency as a function of airflow speeds at the FFU exit. Total pressure efficiency of the FFUs varied considerably from unit to unit. The maximum total pressure efficiency of the tested samples was in the range of 8% to 33%, with FFU operated between 0.2m/s and 0.35 m/s of airflow speeds.

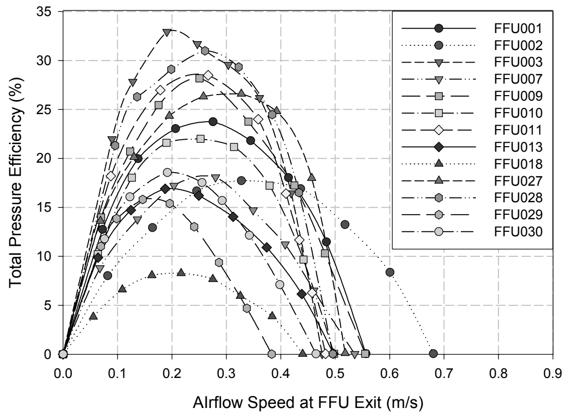

Figure 3. 4’x2’ FFU total pressure efficiency vs. airflow speed at FFU exit

The majority of the 4ft x2 ft units tested in this study were able to produce airflow within the range of 0.30 and 0.50 m/s, which is typical in cleanroom applications, at a static pressure of about 100 Pa (or about 0.4 inch water). In an earlier study [3], only about half of the 20 sample units (in use before 2001) could produce airflow speeds within the range of 0.30 and 0.50 m/s at the same static pressure of 100 Pa (or about 0.4 inch water). Furthermore, the median total pressure efficiency of those units was less than 14%. Compared with the results from the earlier study, Figure 2 and Figure 3 indicate some improvement in the aerodynamic performance of these FFUs over their previous counterparts. The trend of improvement probably is attributed to a combination of factors such as technology improvement of individual FFU components, improvement in the assembly of FFUs, and other means that are conducive to design enhancement. By examining the magnitudes of total pressure efficiency in this study, we can see that the efficiency of one unit could be two-to-three-times as much as others at a typical test condition. The best efficiency of these FFUs at a common operation speed of, say, 0.4m/s, is around 25%, which was not surprisingly lower than that of a regular industrial fan with approximately the same capacity.

Based upon the above analysis, it is clear that there are considerable variations in the FFUs’ aerodynamic performance from product to product. It is also clear that opportunities exist for some FFU suppliers to improve FFU aerodynamic performance.

2. Energy Performance Index (EPI)

In order to evaluate the energy performance of FFUs, it is necessary to specify certain test conditions and to examine the performance metrics accordingly. The following presents EPI, namely electricity power intensity (watts per m^3/min, or W/cfm), corresponding to certain testing conditions for the FFUs tested.

For instance, given a specific static pressure rise, it is possible that actual airflow rates are different among various FFUs; therefore, the calculated EPI value of an FFU would be likely based upon an airflow rate different from others. The advantage of fixing the static pressure rise at a certain level (e.g., 125 Pa) is to allow a direct EPI comparison regardless of differences in air systems in which FFUs would actually be installed.

Figure 4 shows the EPI values for the thirteen 4 ft x 2 ft FFUs at different static pressures. The median value of the performance index at 125 Pa (or about 0.5 inch water) is approximately 11.3 W per m^3/min (or 0.32 W/cfm), meaning that 50% of the FFUs tested at the inlet static pressure of 125 Pa (or about 0.5 inch water) perform better than 11.3 W per m^3/min (or 0.32 W/cfm). The EPI of an FFU generally increases as the pressure increases. An FFU ranking higher at 125 Pa does not necessarily rank higher at other pressures. When selecting FFUs for a specific application, one should also be aware of the actual flow rates that the FFUs can provide at a certain pressure.

Overall, the differences between the unit’s EPI values can be three times as much under certain operating conditions. This indicates that there is potential for many of the FFU suppliers to improve FFU energy performance. It also indicates that there is an opportunity for users to select more efficient units as a means of improving the performance of their cleanroom systems.

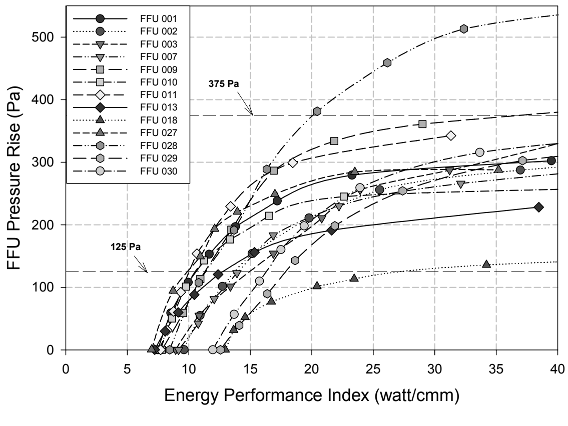

Figure 4. 4’x2’ FFU pressure rise vs. EPI (power intensity)

3. FFU Sizes

To examine the effect of FFU sizes, parallel tests were conducted for seven 4 ft x 4 ft FFUs. Figure 5 shows the pressure rise curves of these 4 ft x 4 ft FFUs. Similar to Figure 2, Figure 5 shows static pressure rises as a function of airflow speeds. In general, the magnitudes of pressure rises of these 4 ft x 4 ft FFUs are similar to those of the thirteen 4 ft x 2 ft FFUs tested at similar airflow speeds. This indicates that given a same pressure rise, 4 ft x 4 ft FFUs may provide much higher airflow rates.

One would expect better efficiency for FFUs with less resistance in airflow pathways, if given that other parameters are similar. In the cases of 4 ft x 4 ft FFUs, EPI values are expected to be lower (better performance) at a given pressure rise than those of 4 ft x 2 ft FFUs. Figure 6 shows the EPI of 4 ft x 4 ft FFUs tested in this survey. The EPI at 125 Pa falls in the range of 7.5 watts per m^3/min (or 0.21 W/cfm) to 13.5 watts per m^3/min (or 0.38 W/cfm), with the median value of less than 8.0 watts per m^3/min (or 0.23 W/cfm), which is much lower (more efficient) than that of the 4 ft x 2 ft FFUs (11.3 watts per m^3/min, or 0.32 W/cfm).

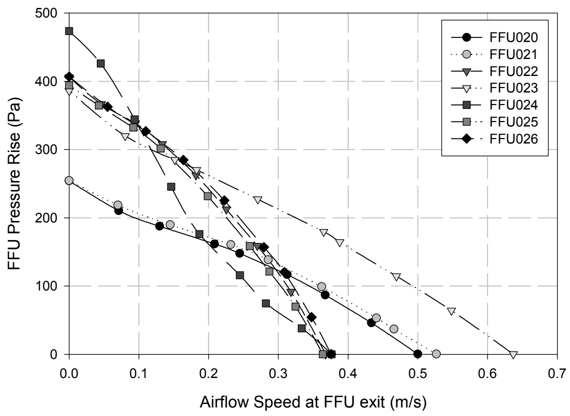

Figure 5. 4'x4' FFU pressure rise vs. airflow speed at exit

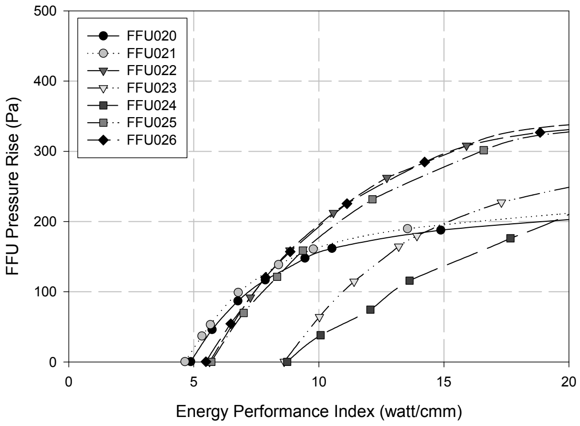

Figure 6. 4'x4' FFU pressure rise vs. EPI (power intensity)

Discussion

Having a method for consistently testing and reporting the energy performance of fan-filter units, FFU suppliers can compare their units to their competitors. Cleanroom owners and designers can also make informed decision regarding energy usage and efficiency when FFUs are required. For instance, they can use EPI as an input parameter in their life-cycle-cost analysis.

The new laboratory method for determining energy performance developed at LBNL requires a setup that is similar to the existing ITRI setup, which is consistent with the ASHRAE/AMCA standard in measuring airflow rates [4]. We expect significant benefits of having such a method in place and used by the industry:

- An immediate success will be to provide comparable performance information to users and designers to make informed decisions such as selecting more energy efficient models;
- Market transformation toward "green" systems in cleanrooms could be accelerated through utility incentive programs based upon measured performance data. Utilities and other public interest programs promoting energy efficiency may be able to encourage use of more energy efficient models. Another ripple effect would be that suppliers would be encouraged to pursue innovative FFU designs that are greener and more energy efficient.
- This will benefit current industry activities to develop an FFU testing guideline. In fact, IEST Working Group (WG) 36 is starting to develop a recommended practice guideline for testing overall performance of FFUs, with a broader scope. The IEST WG will integrate the LBNL laboratory testing method in its guide development.

Conclusions and Recommendations

Laboratory testing of FFU energy performance can provide useful data for suppliers and end users to understand the performance of FFU products. The advantage of establishing such a consistent testing and evaluation method is to provide better comparisons and understanding of FFU performance. New performance information produced in this manner can suggest good practices and energy-saving opportunities when FFUs are required. We recommend using energy metrics such as EPI; and have found better EPI values for larger (4 ft x 4 ft) FFUs.

The results are based upon a sample of new FFU products (4 ft x 2 ft and 4 ft x 4 ft) in the market, including ten 4 ft x 2 ft FFUs reported in a recent paper [10]. In order to develop a baseline for ranking energy performance, e.g., median values of EPI, a larger sample size of FFUs is needed. To achieve a "greener" cleanroom facility while satisfying contamination control requirements, future efforts may include 1) conducting tests of additional FFUs with various types, controls, and designs; 2) improving FFU designs through investigating additional factors contributing to actual performance levels, such as motor types, and fan wheels design in FFUs; 3) providing assistance to users and electric utilities to formulate incentive programs for adopting more efficient FFUs in cleanroom applications; and 4) establishing an industry recommended practice guideline and an international standard.

Acknowledgements

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