LBNL- 61684

Demonstration of Advanced Filtration Technologies:

Developing Energy-rebate Criteria through Performing Standard Laboratory Tests and Statistical Analyses

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Disclaimer

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1. Abstract

Fan-filter unit systems used for re-circulating clean air in cleanrooms are gaining popularity in California as well as in rest of the world. Under normal operation, fan-filter units require high power demand, typically ranging from 100 to 300 W per square meter of cleanroom floor area (or approximately 10-30 W/ft^2). Operating 7 by 24, they normally consume significant electric energy, while providing required contamination control for cleanrooms in various industries. Previous studies focused on development of a standard test procedure for fan-filter units. This project is to improve the methods, and develop new information to demonstrate the methods can be used to assist the industries to apply more energy-efficient fan-filter units in cleanrooms.

Specifically, this project expands previous developmental activities of a test protocol to characterize a pool of 17-sample fan-filter units (FFUs) recruited from Asia, Europe and North America. Through laboratory experiments and modeling characterization, the project develop and demonstrate means of identifying and applying existing or new filtration technologies with higher energy efficiency in the market. All the FFUs had a nominal size of 61-cm-by-122-cm (2-ft by 4-ft). We established a new testing facility, performed new laboratory test using a refined test method, conducted data analyses, developed models to characterize energy performance of the 17 FFUs. Based upon the laboratory test results, we developed a relative ranking system to compare energy efficiency of the FFUs, and recommended options of formulating initial energy-incentive criteria for consideration and use in utility companies' future rebate programs.

The refined standard methods including the test procedure and regression models were used to characterize dynamic operation of individual fan filter units. Based upon the laboratory results, options for initial energy-incentive criteria are developed for utility companies. The new rebate program(s) can then become a strategic means to identify and promote applications of energy efficient FFUs. In addition, the results can also be used for future product development toward higher-efficiency. FFUs with higher energy performance are identified in the project, which also demonstrates that significant reduction in energy use in cleanroom systems is possible through

adopting energy efficient FFUs. Lastly, this report provides recommendations for future research, development, and implementation of high-performance FFUs.

2. Background

Cleanrooms are essential to a variety of industries important to the state's economy. Cleanroom facilities are characterized by large base-loads operating 24 hours a day with energy intensities much higher than typical commercial buildings. Recognizing that energy consumed by cleanroom buildings in California represents an attractive opportunity for energy savings, Lawrence Berkeley National Laboratory (LBNL) performed research and outreach activities in this sector, and developed technologies, tools, and strategies addressing various aspects of the overall efficiency opportunity in cleanrooms.[1]

In the course to reach their energy savings potential, we have identified areas such as fan-filter unit systems used in re-circulating clean air in cleanrooms. Prior project focused on development of a draft standard test procedure for fan-filter units. FFUs are gaining popularity for use in California cleanrooms as well as in rest of the world. Demonstration of energy efficient filtration technologies is vital to improve application of existing or new energy-efficient technologies and to develop strategies to transform the market toward higher energy efficiency.

The overarching goal of the research was to improve the energy efficiency of cleanrooms and to increase energy savings and demand savings in cleanroom systems. This would provide financial and energy benefits to California companies. Specifically, this project expands the development and outreach activities to promote energy efficiency for cleanrooms that use 61-cm-by-122-cm (2'-by-4') fan-filter units, through demonstrating the development of new standard methods to characterize FFUs, and application in developing energy-rebate program criteria.

3. Goals and Tasks

This project's goal is to demonstrate energy-efficient fan-filter technologies through utilizing the new standard methods developed by LBNL.[2][3] The main tasks were

- to refine the methods to characterize fan-filter unit operation under various control setting,
- to carry out fan-filter tests and to document test procedure
- to develop mathematical models for characterizing FFU energy performance
- to design and conduct additional experiments to improve understanding and robustness of the standard methods developed in this project.

Based upon the data gathered from laboratory tests and modeling, technical information was analyzed and developed. The developed information is expected to quantify energy efficiency of FFUs available in the cleanroom market, and to engage the industries including utility companies, end-users, and suppliers in promoting use of energy efficient FFUs. The results can suggest options of to recommending criteria for possible utility energy incentive programs to promote applications of energy efficient fan-filter technologies.

4. Project activities and deliverables

In order to achieve the goals, we designed and assembled a new test rig with a data acquisition system as the test facility at LBNL. We used the initial test rig to measure and evaluate functionality and performance of 17 fan-filter units. The draft test method was refined and used in this round of experiments. In the new version of standard methods, we developed and included the documentation on equipment requirements (e.g., accuracy and calibration), test rig setup and integrity diagnostics, and details of the testing procedure. The contents of new document have been continuously refined and improved through numerous experimental trials and errors.

In addition, we have been working with industry organizations (e.g., IEST, AMCA, CleanRooms Magazine, and Controlled Environments Magazine) to attempt to gain industry acceptance of the standard methods. In particular, these two leading magazines - CleanRooms Magazine, Controlled Environments Magazines supported the R&D effort by providing free of charge support, i.e., periodic calls for industry participation and updates of the FFU project. Because of collaboration, we have received a number of in-kind support from suppliers and users of FFUs in Asia, Europe, and North America.

In the meanwhile, we continued interactions with IEST contamination control division and working group committee – "WG036 Testing Fan Filter Unit." IEST is an ANSI-accredited organization actively in developing and publishing industrial standards such as RPs that guide practices in cleanroom and controlled environments. The IEST WG 036 committee consists of approximately twenty professionals associated with the industries, standard-setting entities including AMCA, ASHRAE, and government. Over the last two years, the committees were informed of the project outcomes and were engaged in providing comments. So far, the committee has been open to integrate the refined methods and procedures in a new Recommended Practice expected to be accepted and published by ANSI-Accredited IEST. The draft standard [1][2] to characterize energy performance of fan-filter units was approved and adopted by the Working Group 036 (WG036) of IEST Contamination Control Division in its Recommended Practice (RP) Draft. We also communicate with AMCA, which is awaiting official publication of Recommended Practice by IEST. The final publication timeline of RP036.1 is unclear but the committee is planning to vote the RP in November 2007. If approved, the document will undergo editorial work followed by the approval of the IEST Executive Board.

In this phase of research and demonstration, we have developed new characterization methods using new regression models to characterize energy performance of individual fan filter units. The new models allow users to quantify unit's efficiency and power demand levels and functionality. Through additional data analyses, we have developed two options of feasible energy-rebate criteria for the use of California utilities in their possible energy-incentive programs.

At the onset of the project, we evaluated advantages and disadvantages of possible test facilities (e.g., PG&E's Thermal Flux Energy Test Facility in San Ramon, UC Berkeley campus, ITRI – AMCA certified facility in Taiwan, AMCA headquarters facility in Illinois, and other testing labs). As a result, we designed and constructed of an FFU test rig and established a data acquisition system at LBNL Building 63 laboratory space. We then performed calibration and troubling-shooting of the test device, and conducted leakage tests of the FFU test rig at LBNL. Pilot tests and experiments were designed and conducted to identify potential deficiencies or pitfalls of the new test rig or equipment. We improved and validated the integrity of the test rig and identified measurement accuracies of devices.

A standard method in place will enable consistently characterizing and reporting the energy performance of fan-filter units (FFUs). LBNL carried out protocol development, performed experiments and evaluations on various fan-filter units, developed modeling methods to quantify FFU performance, and generated comparative performance information of fan-filter units. [5][6][7][8] [9] during the course of this project, we refined the methods and procedures to include more details and specific guidance as part of the standard methods. The new standard methods include mathematical regression modeling to characterize individual fan filter unit's energy performance and functionality based upon the laboratory work.

Using the new standard methods allows characterizing various FFU models or products, which in turn will help manufacturers to better understand their products, and assist cleanroom owners and designers to make informed decisions concerning selection of fan-filter units for re-circulation systems. In addition, performance data generated by the standardized testing may be used to establish l performance rating criteria should they be desired or needed by interested parties. For example, energy efficiency practice may be encouraged through utility incentive programs, which may be established based upon quantitative information from the standard laboratory tests, modeling, and statistical analyses.

We performed a series of laboratory experiments and mathematical modeling to characterize efficiency of seventeen fan-filter units, which were recruited from and donated by the industries in Asia, Europe, and North America (Canada, USA). We also conducted statistical analyses and modeling to develop a relative ranking system. Using the relative ranking system and measured performance, we have developed options for establishing initial energy-rebate criteria. The criteria can be easily used to identify higher-performers of fan-filter units for rebate qualifications, or to estimate cost effectiveness of efficient and functional units under specific operating conditions as desired by designer, owner, and the utility company to be involved in determining the magnitude of incentive.

Project activities and deliverables are described in the following:

- Completed the design, construction, and commission of the test rig, we completed the assembling of data acquisition systems and performed trouble-shooting of the test device and facility at LBNL.

- Interacted with two leading magazines – Cleanroom Magazine and Controlled Environments: 1) announcing the demonstration project and recruiting participants and units, 2) providing updates and outcomes of the project. For example, Controlled Environment Magazine (November 2005, April 2006, November 2006) and Cleanrooms Magazine (December 2005 – March 2006, October 2006 - November 2006) reported news and/or outcomes on the PIER/LBNL FFU project. The FFU work under PIER was among the top stories of online news or Contamination Control Newsletter in February, March, October, and November 2006 (Cleanrooms Magazine). We obtained 17 fan-filter units free of charge from the anonymous industrial participants including suppliers and users of fan-filter units. Confidentiality agreements were reached between participants and LBNL. Unless permitted by the participants, the final report and future publications of the test information will not identify any of fan-filter manufacturers or products by name.

- Through interactions with the industry, including suppliers, users, and IEST, LBNL received eighteen 61-cm x 122-cm (2-foot x 4-foot) FFUs, selected, and completed the laboratory tests of seventeen FFUs. We have completed testing two extra units than originally budgeted and allocated within this phase of demonstration.

- Held meetings with PG&E to report project results and discuss ways to be used by PG&E. We presented and disseminated up-to-date test results to PG&E, arranged meetings and discussed options for possible rebate programs to be offered by PG&E, and enlisted recommendations for further R&D beyond this demonstration project.

- Interacted with users and suppliers to promote the use of the standard test method developed at LBNL. Interacted with a number of FFU manufacturers and users concerning their participation in the FFU demonstration project to improve the understanding of FFUs' energy performance and means to save energy. Seagate and Texas Instrument actually required FFU suppliers to provide test results by adopting the LBNL standard method to evaluate energy efficiency of fan-filter units. Several manufacturers are interested in participating in test bigger units, e.g., 122-cm x 122-cm (4-foot x 4-foot) FFUs. The participant in this project includes manufacturers from Asia, Canada, Europe, and US and an end-user in California.

- Performed data analysis, developed, refined, and finalized a module for reporting performance of individual FFUs to participants of the units. As part of agreement with fan-filter suppliers, LBNL produced 17 individual confidential reports and delivered them to the participants who donated their FFUs, respectively. The manufacturers and users participating in the demonstration project are now able to obtain the electric power demand under any operating conditions within the tested range and will be able to compare with other units under a selected operating condition.

- Disseminated publications (research papers and the draft standard test method) to the industry and the project participants.

  - T. Xu participated in IEST's regular WG meetings on "Testing Fan Filter Units,' and has been reinforcing the adoption of measurement methods in the LBNL standard test method.

  - T. Xu offered a tutorial class on applications of energy efficient fan-filter units at ESTECH 2006.

  - LBNL hosted laboratory visits by PG&E, CEC, ITRI, PNNL, EPA, and other project participants.

  - T. Xu present project findings at a PG&E workshop in November 2006.

- LBNL refined the existing draft standard test method (version 1.3, 2005), based upon the additional questions or comments provided by end-users and manufacturers, and the new knowledge and experience gained throughout the experiments in this phase of demonstration tests. LBNL updated the draft standard test procedure for testing fan-filter units, and made it (Version 3.0, 2007) available in the LBNL web page. The documents have stimulated significant interests from the stakeholders including users, suppliers, and IEST, the latter of which has voted to accept test methods of airflow rates, pressure, and electric power.

- LBNL developed technical information to compare FFU energy performance based upon the test data. LBNL performed a series of statistical analyses to quantify performance variation across units and operating conditions, and developed a relative ranking system. The relative ranking system is used to establish energy-rebate criteria for possible use by utility companies in establishing a rebate program. Along with the draft final report on findings, an invited article on the current study was published in Cleanrooms Magazine (November 2006), and project updates appeared in Cleanrooms Magazine, Contamination Control Newsletter, and Controlled Environments Magazine.

- Prepare a draft report of findings following completion of the testing for inclusion as an attachment to the final report.

Much of the energy in cleanrooms (and minienvironments) is consumed by 61-cm x 122-cm (2-foot x 4-foot) fan-filter units-typically located in the cleanroom ceiling (25-100% coverage)-which deliver re-circulated air to the clean spaces. LBNL has developed the first-ever standard energy test method for FFUs, which is being adopted by IEST Working Group 36 as a critical portion of industry standard- IEST RP CC036.1.

5. Report on Findings

5.1 Objective

The main objective of the project is to develop a testing rig and data acquisition, and use the new rig to characterize energy performance of 17 fan-filter units using the draft standard method developed at Lawrence Berkeley National Laboratory [1] in LBNL's Building 63 facility. In addition, we designed and conducted additional experiments to evaluate and improve the robustness of the standard methods including the laboratory testing method, equipment requirements, procedures, and modeling methods. Furthermore, additional data analysis was conducted to provide recommendations for options that utility companies can use for possible rebate programs to encourage the use of energy efficient FFUs.

One of the important outcomes from this project was to develop, refine, and publish an updated, standalone standard method for characterizing energy performance of fan-filter unit, including testing methods, procedures, and performance modeling based upon laboratory data. This report will 1) describe test setup of the demonstration at LBNL, 2) summarize results from experimenting 17 sample fan-filter units using the standard methods being updated, 3) evaluate repeatability of laboratory testing under a variety of conditions, and 4) develop options of energy-rebate criteria based upon the test results and statistical analyses. The energy-rebate criteria can be for the use of utilities in designing rebate programs to promote implementation of FFUs that are more energy efficient.

5.2 Designing Test Rig

Prior to the study, we reviewed open literature including ISO Standards, ASHRAE Standards including AMCA/ASHRAE Standard 51.2. These standards address the requirements for measuring airflow rate and air pressures associated with different HVAC equipment in ducted or un-ducted testing layouts. Some of the standards are applicable to characterize fan performance, or air conditioners in various laboratory setting. For example, fan performance characterization requires large chambers and flow baffles to create uniform airflows entering the fans. However, none of these standards specifically addresses any method for characterizing fan filter units or provides any direct guideline on acceptable laboratory methods or testing rigs to characterize electric power demand, airflow rate, and pressure differential across a fan filter unit in different operation.

An initial test rig was designed, constructed, commissioned in a laboratory of LBNL. The test rig was used to conduct laboratory testing of 17 FFUs recruited from the market. The test rig was also used and adapted to perform additional experiments on selected FFUs in this study. The Appendix Section includes details of the test rig material, sizes of components, sensor locations, and equipment. Additionally, we assessed and refined the existing test methods through numerous trials and errors. The analyses and evaluations of date produced from the laboratory testing and experiments have created new information on FFU performance, new knowledge of the robustness of various test rig design and device setting, and validated laboratory methods, test procedures, and mathematical characterization of dynamic operation of FFUs. The new standard methods including the testing procedures were developed, and were published separately in the updated, refined standard document [3].

5.2.1 Sample fan-filter unit

Most of the individual FFU samples recruited and used in the demonstration project consisted of a small fan, and a HEPA or ULPA filter, and a sealed box sized to fit into standard cleanroom ceiling grids 61-cm by 122-cm (2 ft by 4 ft) as shown in Figure 1. One of the units has dual identical motors and fan wheels that are placed symmetrically inside the 61-cm x 122-cm (2-foot x 4-foot) FFU.

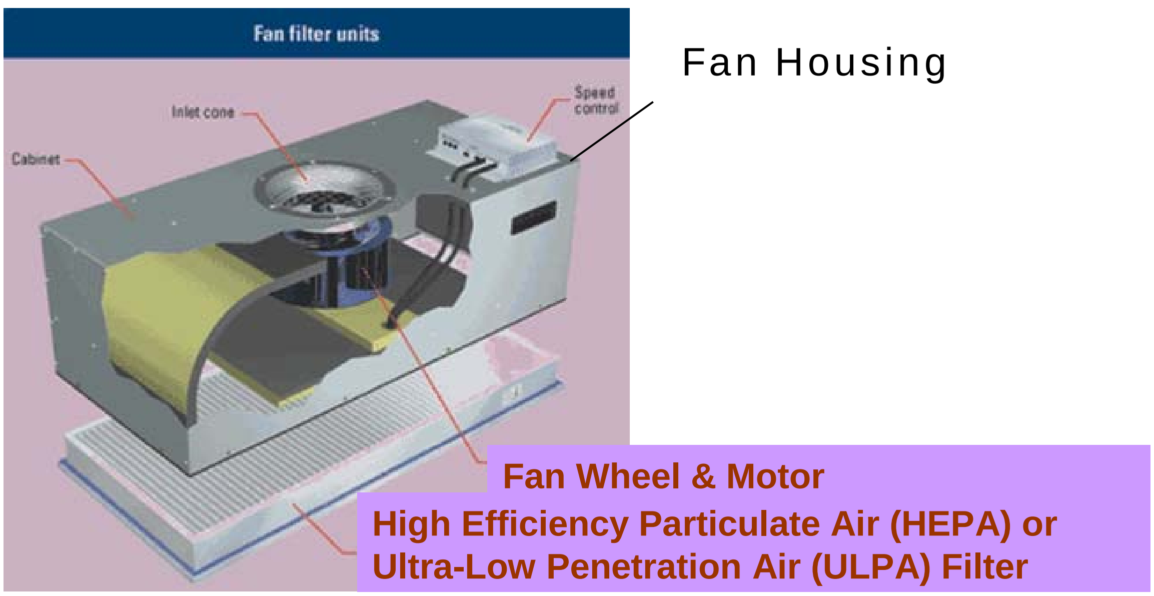

Figure 1 Generic Structure of 61-cm-by-122-cm Fan-filter Unit

5.2.2 Designing test rig

An initial test rig was designed, constructed, and installed according to the test method developed at LBNL. The initial test rig setup contained a combination of requirements by existing ASHRAE/AMCA and ISO Standards. In this test setup, a 61-cm by 122-cm (2 ft by 4 ft) FFU tested was mounted vertically. The FFU inlet was connected at the discharge end of a straight 61-cm by 122-cm (2 ft by 4 ft) ductwork made of galvanized sheet metal. The ductwork was reinforced using metal rods as well as additional wood poles to withstand the force produced by the pressure difference between inside and outside of the duct.

A booster fan and a damper were installed at the ductwork inlet to modulate air pressures across the FFU while the airflow rates were concurrently controlled. Upstream of the 61-cm by 122-cm (2 ft by 4 ft) ductwork, the rig contains a round duct with a diameter of 25 cm (10 inches). The round duct connect to a standard flow straightener leading to a single-nozzle, 25-cm (10-inches) flow meter that is used to record airflow rates through the tested unit. The initial test setup was used to test and evaluate 17 sample FFUs in this study.

Additionally, we investigated the robustness of the test rig in terms of its physical integrity (e.g., leakage), and repeatability of measured performance under various test rig designs. Specifically, we changed various test rig setting and refined the methods to conduct experiments to evaluate repeatability and explore means to improve consistency. For example, we developed new information through designing and conducting additional experiments while changing test rig sizes and device locations. As a result, analysis of experimental data and information provided better understanding of measurement techniques for airflow rates, pressure change, power demand, and efficiency levels. The results from experimenting and analysis quantified the sensitivity of measured performance to variation in laboratory conditions, such as test rig sizes, locations of pressure taps, air temperatures.

5.3 Developing and Refining Laboratory Method and Procedure

The unit airflow rate, fan-wheel rotational speed, pressure differential across the FFU, and total electric power demand were recorded concurrently at any given operating condition. The operating conditions selected for testing covered typical operating conditions of each unit. Each of the operating conditions was achieved by adjusting the assisting fan wheel speed, the position of the damper installed in the test rig, and speed-control setting (if any) of fan filter unit. Normally, continuous adjustments of the device setting are essential to achieve a range of operating conditions defined by the pressure differential across the unit and the actual airflow rates of the fan filter unit.

In order to generate various testing conditions, the pressure differentials across FFU were normally controlled at various levels for each RPM setting. For example, within each incremental RPM setting, pressure differential was set to be as low as zero to 0.2-inch water column (0-50 Pa) up to 1.5-inch water (375 Pa), when applicable. The total power demand and performance metrics were then obtained for a specific operating condition and/or a specific range of operating condition, e.g., pressure differential of 0.5-inch water (125 Pa) coupled with and actual unit airflow rate of 520 cfm (245 Ls^{-1})) that the unit was capable of supplying. The FFU modulation device when applicable was integrated with the FFU for setting fan-wheel rotation speeds (Rotation per Minute, RPM). In these cases, the fan-wheel motor in the FFU was set at different RPMs during the testing to obtain performance data. At each RPM setting, the FFU was tested at various pressure-rise across the unit, which was modulated by adjusting Iris damper positions. The ambient conditions and the airflow conditions were recorded and were used for the air density conversion to the equivalent standard condition (i.e., 1 atm, 20°C). We assume that the airflow was isothermal, although a small fraction of heat was generated from fan motors, which was transferred to the airflow. The reported performance data were based upon the standard air condition, i.e., with the air density of 1.20 kg/m^3, in order to directly compare the energy and aerodynamic performance. More details of testing methods, procedures, and device were described in appendices and the updated standard methods.

5.4 Developing Polynomial Regression Models to Characterize Energy Performance

Based upon the test results, we analyzed individual unit's functionality. i.e., operable conditions, and developed mathematical models to characterize dynamic operation and energy performance of individual fan-filter units.

Specifically, total electric power demand and total pressure efficiency were used as the yardsticks for quantifying unit's energy performance. The main approach was to develop polynomial regression models to quantify total power demand and total pressure efficiency of the individual units corresponding to their applicable operable conditions. The models characterize the relationship among energy performance metrics, airflow rates, and pressure differential across the units.

An FFU's total electric power demand includes power demand for fan motor, transformer, speed controller and display, and any accessories attached to the unit. Total electric power demand was measured using a power meter for selected operating conditions. To characterize total electric power demand, a polynomial regression model was established based upon laboratory test data, as it relates to actual operating conditions that are defined by unit airflow rates and pressure differential across the unit. For FFUs with a single-speed drive, the total electric power demand can be calculated using either of the following equations.

$$W_t = C_0 + C_1 \cdot D_p + C_2 \cdot D_p^2, \text{ or } W_t = C_0 + C_1 \cdot Q + C_2 \cdot Q^2$$

Where

D_p is the pressure differential across the fan filter unit.

Q is the airflow rate across the unit under standard atmospheric condition.

C_i (i = 0, 1, 2) is a coefficient developed from experimental data through polynomial regressions.

For FFUs with a multi-speed-drive, total electric power demand can be calculated using the following equation.

$$Wt = C0 + C1 \cdot Dp + C2 \cdot Q + C11 \cdot Dp^2 + C12 \cdot Dp \cdot Q + C22 \cdot Q^2$$

Where

Dp is the pressure differential across the fan filter unit

Q is the airflow rate across the unit under standard atmospheric condition.

$C_{i,j}$ (i, j = 0, 1, 2) is a coefficient developed from experimental data through polynomial regression.

An FFU's total FFU pressure efficiency (η_t) is defined as the actual airflow pressure power divided by the total electric power input to the FFU unit. Total pressure efficiency was calculated based upon laboratory test data, as it relates to operating conditions that are defined by unit airflow rates and pressure differential. For FFUs with a single-speed drive, total pressure efficiency can be calculated using either of the following equations.

$$\eta_t = \frac{Q \cdot D_p}{C_0 + C_1 \cdot D_p + C_2 \cdot D_p^2}, \text{ or } \eta_t = \frac{Q \cdot D_p}{C_0 + C_1 \cdot Q + C_2 \cdot Q^2}$$

Where

D_p is the pressure differential across the fan filter unit.

Q is the airflow rate across the unit under standard atmospheric condition.

C_i (i = 0, 1, 2) is a coefficient developed from experimental data through polynomial regressions.

For FFUs with a multi-speed-drive, the total pressure efficiency may be calculated using the following equation.

$$\eta_t = \frac{Q \cdot D_p}{C_0 + C_1 \cdot D_p + C_2 \cdot Q + C_{11} D_p^2 + C_{12} \cdot D_p \cdot Q + C_{22} \cdot Q^2}$$

Where

D_p is the pressure differential across the fan filter unit

Q is the airflow rate across the unit under standard atmospheric condition.

$C_{i,j}$ (i, j = 0, 1, 2) is a coefficient developed from experimental data through polynomial regressions.

5.5 Findings

In this report, we present the following parameters obtained from laboratory characterization, and include information for performance reporting: Unit's airflow rates (or airflow speeds), pressures rise across the unit, total electric power demand, and total pressure efficiency.

5.5.1 Airflow rate and pressure differential

Figure 2 shows the measured airflow rate as it related to the air pressure differential across a sample FFU with AC power supply and a multi-speed-drive controller. The measurements were taken while fan-wheel rotation speeds were set at three preset RPM levels sequentially.

It is clear that the FFU pressure differential decreased with the increase in airflow rates within the operating range of the FFU for each RPM setting. In addition, the FFU pressure differential across the unit was higher with the higher RPM at any given airflow rate. Similarly, for a given airflow rate, pressure differential across the FFU was maximized by operating the unit at its highest setting for fan-wheel's speed control.

Different from the sample unit shown in Figure 2, Figure 3 shows measured airflow rate as it related to the air pressure differential across another sample FFU with an electric commuted DC motor and a variable-speed-drive speed controller. The measurements were taken while fan-wheel rotation speeds were being set at five different levels respectively.

It is clear that the FFU pressure differential decreased with the increase in airflow rates within the operating range of the FFU for each speed-control RPM setting. In addition, FFU pressure differential across the unit was higher with the higher RPM at any given airflow rate. Similarly, for a given airflow rate, the pressure differential across the FFU was maximized by operating the unit at its highest setting for fan-wheel's speed control.

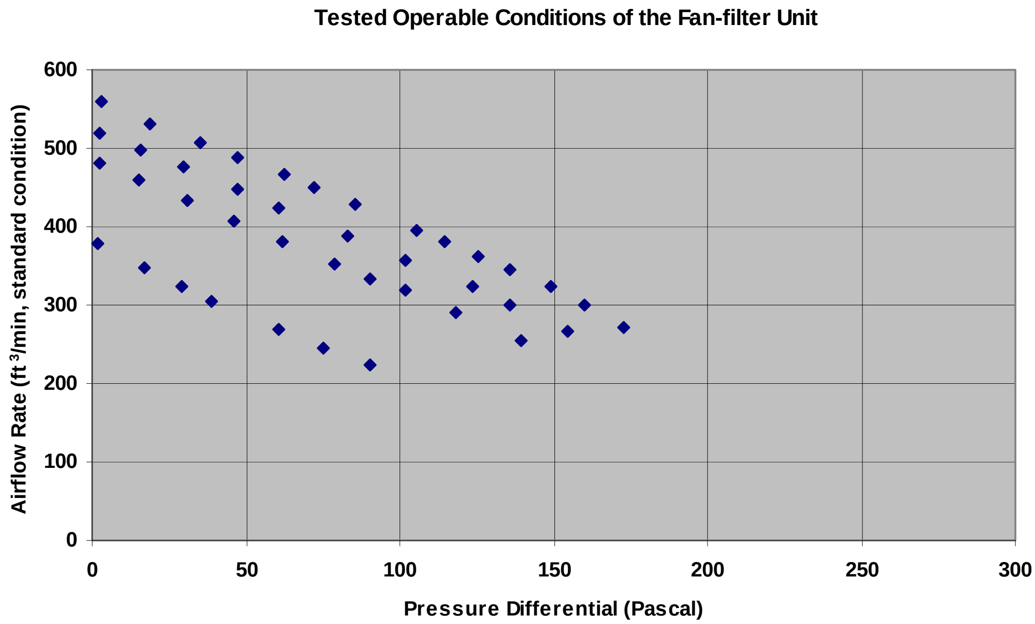

Figure 2 Airflow Rates vs. Pressure Differential (FFU Sample A)

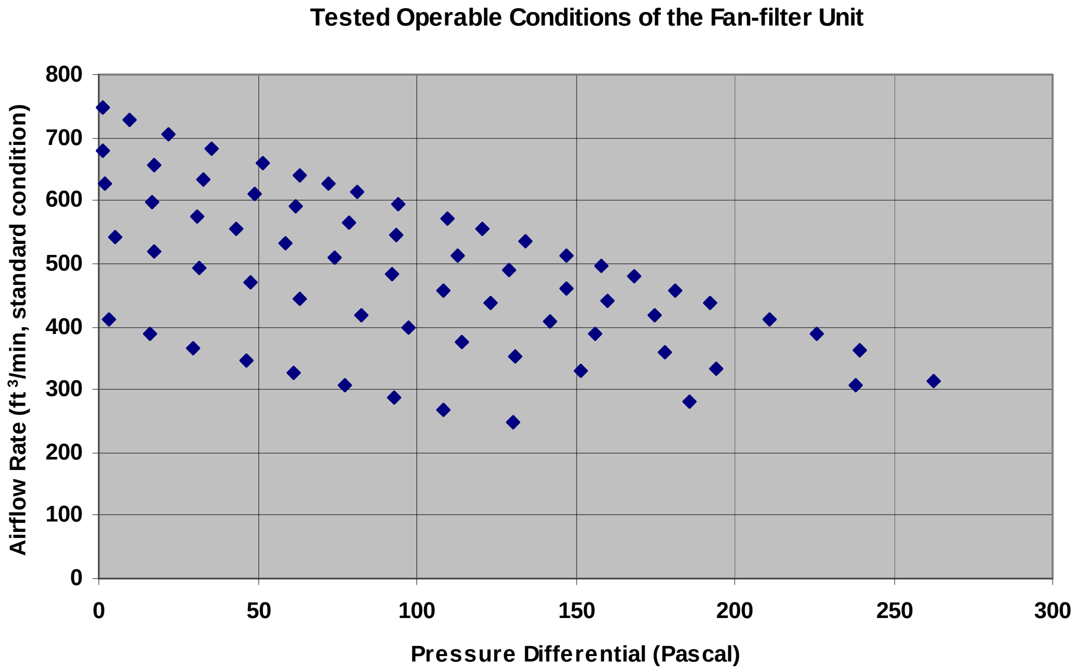

Figure 3 Airflow Rate and Pressure Differential (FFU Sample B)

5.5.2 Total electric power demand

An FFU's total electric power demand includes power demand for fan motor, transformer, speed controller and display, and any accessories attached to the unit.

Figure 4 shows the measured total electric power demand as it corresponded to the airflow rates and pressure differential across a sample FFU (Sample A). Sample A has an AC power supply and a multi-speed-drive controller. Each line in the figure represents the contour of the equivalent electric power demand within the selected operable conditions: 20 Pa ≤ Dp ≤ 150 Pa, Q ≥ 9.9 m3/min (or 0.08-iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm).

Figure 4 shows that Sample A's total electric power demand generally increased with the increase in airflow rates as well as decrease in pressure differential across the unit. Another finding is that total electric power demand was higher with the higher RPM at any given airflow rates and pressure differential within the FFU's operating range.

Figure 5 shows measured airflow rate as it related to the air pressure differential across another sample FFU (Sample B). Sample B has an AC power supply and a variable-speed-drive controller. Each line in the graph represents the contour of the equivalent electric power demand under the selected operable conditions: 20 Pa $\leq$ Dp $\leq$ 150 Pa, Q $\geq$ 9.9 m3/min (or 0.08-iwc $\leq$ Dp $\leq$ 0.6 iwc, Q $\geq$ 350 scfm).

Figure 5 shows that Sample B's total electric power demand generally increased with the increase in airflow rates as well as decrease in pressure differential across the unit. Compared to Sample A shown in Figure 4, Sample B exhibited higher capacity in producing higher airflow rate range as well as pressure differential across the unit. In addition, the increase of total power demand of Sample B was less sensitive to changes in pressure differential and more sensitive to changes in airflow rate. This indicates that the FFU with VSD motor was more receptive to changes in pressure differential - such a unit possesses higher capability to maintain energy demand relatively more constant over variations in external resistance, when everything else remains the same.

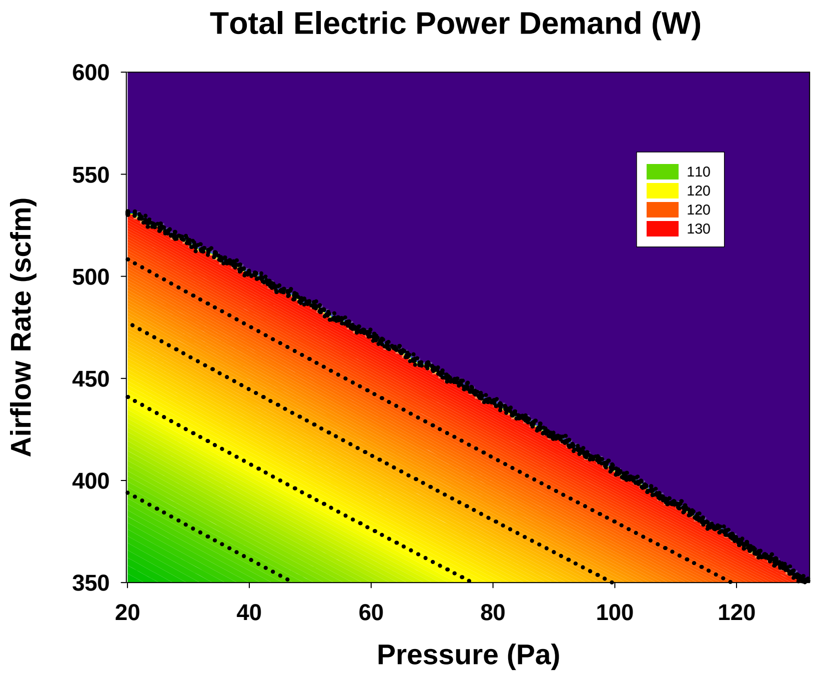

Figure 4 FFU Sample A with multi-speed-drive motor: Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ Dp ≤ 150 Pa, Q ≥ 9.9 m3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)

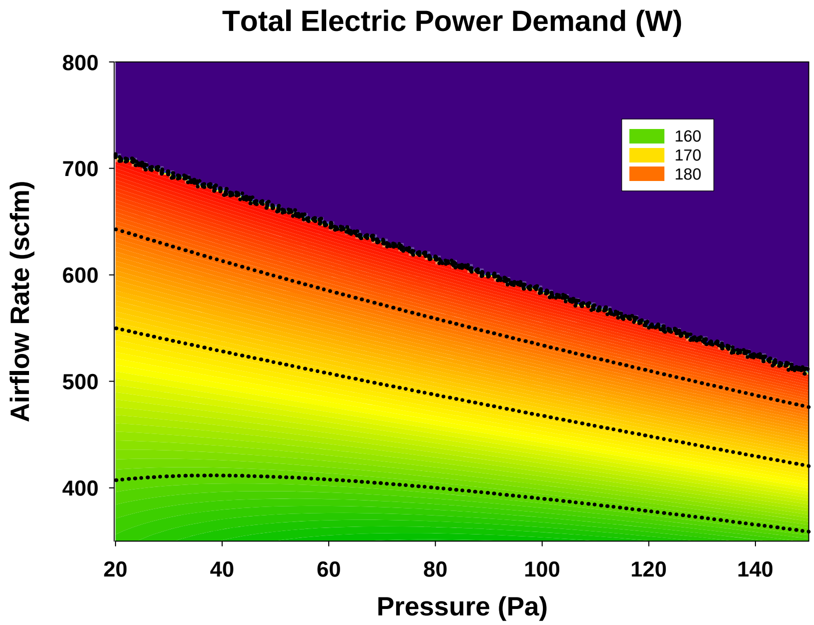

Figure 5 FFU Sample B with various-speed-drive motor: Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ Dp ≤ 150 Pa, Q ≥ 9.9 m3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)

5.5.3 Total pressure efficiency

Total pressure efficiency was calculated based upon laboratory test data, as it relates to operating conditions that are defined by unit airflow rates and pressure differential.

Figure 7 shows the performance curves of the FFU sample A: Total pressure efficiency as it changed with the airflow rates and pressure differential across the unit within a selected range of operating conditions. This sample unit (Sample A) has an AC power supply and a multi-speed-drive controller. Each dotted curve-line in Figure 7 represents the contour of the equivalent total pressure efficiency under selected operable conditions: 20 Pa ≤ Dp ≤ 150 Pa, Q ≥ 9.9 m3/min (or 0.08-iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm).

Figure 7 shows that sample A's total pressure efficiency exhibited a different trend than that of its total electric power demand shown in Figure 4. Total pressure efficiency generally increased with the increase in pressure differential across the unit; however, it remained relatively insensitive to the changes in airflow rates.

We found that the sample FFU's total pressure efficiency exhibited a different trend than that of its total electric power demand: the total pressure efficiency generally increased with the increase in pressure differential across the unit; in the meanwhile, it also increased with increase of airflow rates. However, total pressure efficiency remained less sensitive to the changes in airflow rates at lower pressure differential setting that exhibited at higher-pressure differential.

Figure 8 shows FFU sample B's total pressure efficiency, as it related to the airflow rates and pressure differential across the unit within a selected range of operating conditions. This sample unit has a various-speed-drive controller. Each line in Figure 8 represents the contour of the equivalent total pressure efficiency under selected operable conditions: 20 Pa ≤ Dp ≤ 150 Pa, Q ≥ 9.9 m3/min (or 0.08-iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm).

Figure 8 shows that the sample B's total pressure efficiency also exhibited a different trend than that of its total electric power demand shown in Figure 5. Total pressure efficiency generally increased with the increase in pressure differential across the unit; in the meanwhile, it also increased with increase of airflow rates. However, total pressure efficiency remained less sensitive to the changes in airflow rates at lower pressure differential setting that exhibited at higher-pressure differential.

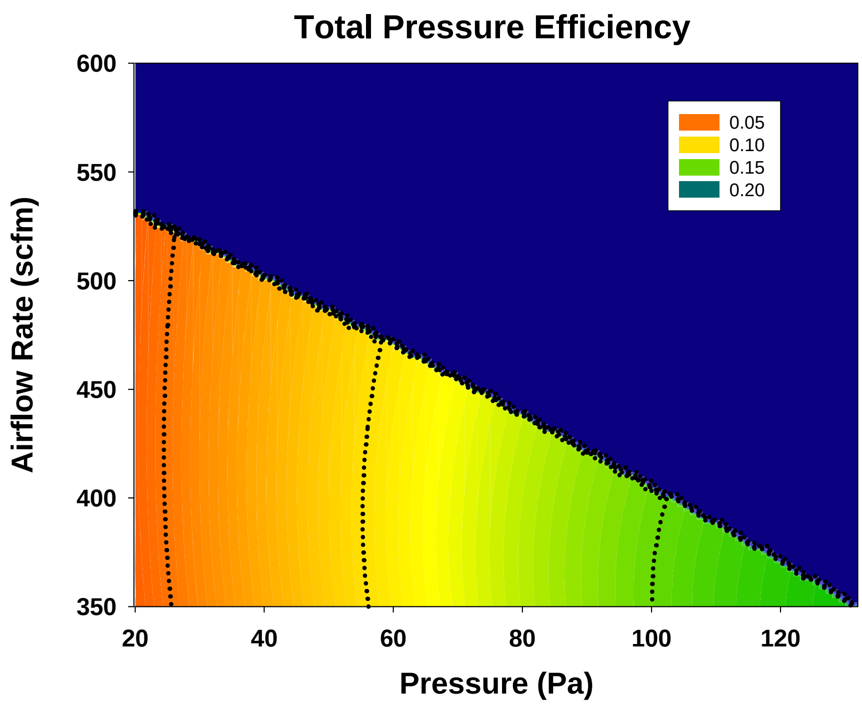

Figure 6

Figure 7 FFU Sample A: Total Pressure Efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ Dp ≤ 150 Pa, Q ≥ 9.9 m3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)

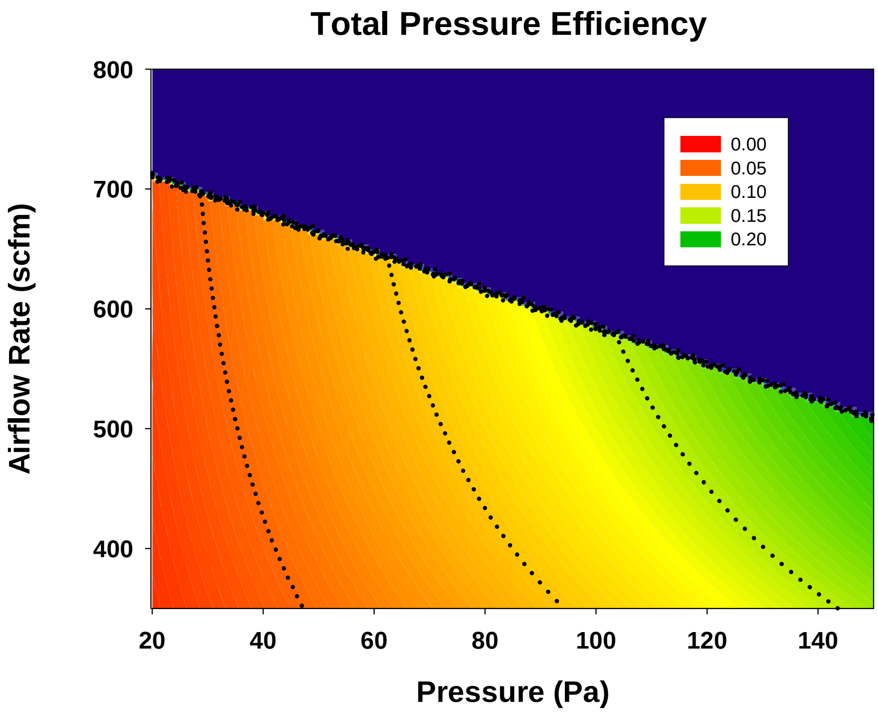

Figure 8 FFU Sample B: Total Pressure Efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ Dp ≤ 150 Pa, Q ≥ 9.9 m3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)

5.5.4 Summary of findings

Using the standard test method, we have performed laboratory experiments on 17 FFUs donated by fan-filter-unit manufacturers in the US, Canada, Europe, and Asia. Operable conditions, total electric power demand, and total pressure efficiency for each individual unit were quantified using the updated standard laboratory test method. The following summarizes the key findings:

The energy performance of each FFU, after being tested within its own operable conditions, may be characterized and mathematically quantified as a function of operating conditions. The operating condition is defined by airflow rate and air pressure differential across the unit.

Among these we have seen electric power demand ranging from 100 to 400 watts per FFU, and significant variations in efficiencies (in excess of ten-times) depending on actual operating conditions, defined in terms of air flow rates (or velocity) and pressure differential across the unit that represents unit’s capability to overcome pressure loss elsewhere in recirculation system.

The total pressure efficiency at any given operable condition can be obtained through the laboratory experiment and multi-variable regressions. When evaluating unit's efficiency under the same operating condition or the same range of operating conditions, we have observed a factor of three or more variation in energy efficiency across the 17 sample units.

The significant variations across operating conditions and units have posed challenges in defining or using a single performance metric for comparing performance, and applications in energy-incentive programs. The following presents the development of energy-rebate criteria through further statistical analyses, including the methods for percentile-ranking modeling and a relative ranking system, and recommendations for energy-rebate criteria.

5.6 Developing Energy Incentive Criteria

Cleanroom owners and users are a historically unresponsive market to energy efficiency efforts. As one of California's important and leading industries, this unique customer segment warrants additional attention and effort to motivate owners/users to participate in energy efficiency programs. Energy rebate programs are designed specifically to motivate the cleanroom owner, designer, or manager toward selecting and installing energy efficient FFU products. With product offerings suitable for the cleanrooms, energy-incentive program(s) may provide opportunities to serve two distinct beneficiaries of high-performance FFUs: the owner (user) and suppliers of such units.

The following analysis provides options of basis upon which energy rebate program can be established: prescription- and performance-based rebates. Using prescription-based approach, incentives will be paid based on identified products. The program identifies the more energy efficient units in the market and awards certain incentive to buyers of such units. Using performance-based approach, rebates are awarded for deemed savings measures. This will involve evaluations of cost-effectiveness, product price difference. The users and cleanroom designers will need to work with utility companies to estimate savings considering difference in energy savings as related to product premiums and cost effectiveness.

5.6.1 Prescription-based approach

5.6.1.1 Statistical method

In order to understand patterns of performance variations exhibited by sample units using the same test method, a simplified method would be needed to quantify and categorize energy-efficiency baseline information. Such baseline information needs to be sufficiently robust for utility to adopt in their energy-rebate programs.

First, we have performed a series of statistical analyses to evaluate the significance of difference in total pressure efficiency of all units under various combinations of operable conditions or ranges of operable conditions. Then we examined the significance in efficiency differences. In particular, we conduct statistical ANOVA-Tests and t-Tests for groups or pairs of total pressure efficiency developed for the pool of sample units. A relative performance ranking system is then developed to quantify the observed difference and to identify rebate-criteria. The relative ranking scores are used to examine the robustness of the suggested initial rebate criteria. For instance, we can find out which units may get recommendations for rebate vs. which ones should not. Once establishing an initial rebate criteria, users may identify an initial set of units that surpass such criteria.

The following presents the results that are relevant to devising, identification, and recommendations for rebate criteria for utilities' rebate program.

5.6.1.2 Percentile-ranking model

The percentile ranking is a function of an array of data, which is determined by a range of total pressure efficiency data that defines relative standing, and the percentile value in the range [0, 1] - inclusive. The percentile-ranking models return the k^{th} ($k = 0, 100$) percentile of values in the range as exhibited by the total pressure efficiency obtained for all of the sample units tested for a specific range of operating conditions. The 12 sets of operating conditions selected are shown in Table 1 in this report.

Total pressure efficiency of each unit was calculated for 12 sets of operating conditions (selected and specified in Table 1). Statistical percentile-ranking models were established to categorize the magnitudes of total pressure efficiency of the units. These models were used to characterize FFU performance at 12 sets of operating conditions that were defined by airflow rate and pressure differential across the FFUs. In particular, percentile-ranking models were employed to quantify levels of total pressure efficiency corresponding to specific efficiency ranking category that is determined by incremental percentiles derived from the sample FFUs.

Table 1. 12 selected sets of operating conditions for all FFU Samples

Selected Operable Conditions	Pressure rise (Pa)	Pressure rise (in. water)	Airflow range (m^3/min)	Airflow range (ft^3/min)	Nominal Airflow Speed (m/s)	Nominal Airflow Speed (ft/min)
1	50-150	0.2-0.6	9.1-22.7	320-800	0.2-0.5	40-100
2	75-125	0.3-0.5	9.1-22.7	320-800	0.2-0.5	40-100
3	50-75	0.2-0.3	11.3-18.1	400-640	0.3-0.4	50-80
4	75-100	0.3-0.4	11.3-18.1	400-640	0.3-0.4	50-80
5	100-125	0.4-0.5	11.3-18.1	400-640	0.3-0.4	50-80
6	125-150	0.5-0.6	11.3-18.1	400-640	0.3-0.4	50-80
7	75	0.3	11.3-18.1	400-640	0.3-0.4	50-80
8	100	0.4	11.3-18.1	400-640	0.3-0.4	50-80
9	125	0.5	11.3-18.1	400-640	0.3-0.4	50-80
10	75	0.3	14.7	520	0.3	65
11	100	0.4	14.7	520	0.3	65
12	125	0.5	14.7	520	0.3	65

Table 2 shows the outcomes from percentile-ranking models developed from the sample units' total pressure efficiency under each of the selected operating conditions.

Supplemental to the data shown in Table 2, Figure 9 shows levels of total pressure efficiency as a function of percentile ranking developed from the 17 sample FFUs tested in this study. In general, units with lower ranking, e.g., under 50th percentile (or median) tend to have similar and lower total pressure efficiency. On the other hand, units with higher ranking, e.g., above 50th percentile (or median) tend to exhibit higher total pressure efficiency. The higher efficiency levels also exhibits bigger spread across the incremental percentile ranking. This observation holds true for all operating conditions or ranges of conditions, as illustrated by the polynomial-regressed trend-lines with R-square values higher than 0.99.

Table 2. Percentile ranking of total pressure efficiency

Total Pressure Efficiency	Percentile										
Selected Operable Conditions	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
1	6.6%	7.8%	9.2%	9.4%	10.9%	11.2%	11.9%	12.7%	13.8%	17.8%	22.2%
2	7.5%	8.1%	9.7%	10.1%	11.4%	12.0%	12.5%	13.4%	14.4%	18.3%	22.6%
3	4.9%	5.4%	6.7%	7.1%	8.1%	8.5%	8.8%	9.5%	10.6%	14.3%	18.0%
4	6.3%	7.2%	9.4%	9.5%	10.2%	11.2%	11.8%	11.9%	13.3%	17.4%	22.3%
5	9.2%	10.1%	11.6%	11.8%	12.4%	13.7%	14.0%	14.5%	15.4%	20.2%	25.6%
6	11.0%	11.7%	13.0%	13.3%	13.3%	15.3%	15.8%	16.5%	18.4%	23.0%	28.2%
7	5.9%	6.3%	8.1%	8.4%	9.2%	10.0%	10.4%	10.8%	12.3%	16.0%	20.3%
8	8.1%	9.3%	10.7%	10.8%	11.8%	12.8%	13.0%	13.3%	15.2%	19.1%	24.1%
9	10.2%	10.7%	12.3%	12.6%	13.0%	14.5%	15.0%	15.5%	17.5%	22.1%	27.0%
10	5.9%	6.9%	8.3%	8.6%	8.9%	9.8%	10.6%	10.8%	13.0%	17.2%	20.6%
11	8.1%	8.7%	10.6%	10.8%	11.3%	12.4%	13.4%	14.2%	16.3%	20.5%	24.4%
12	10.3%	10.3%	11.9%	13.3%	13.9%	14.5%	16.3%	17.8%	20.4%	24.0%	27.3%

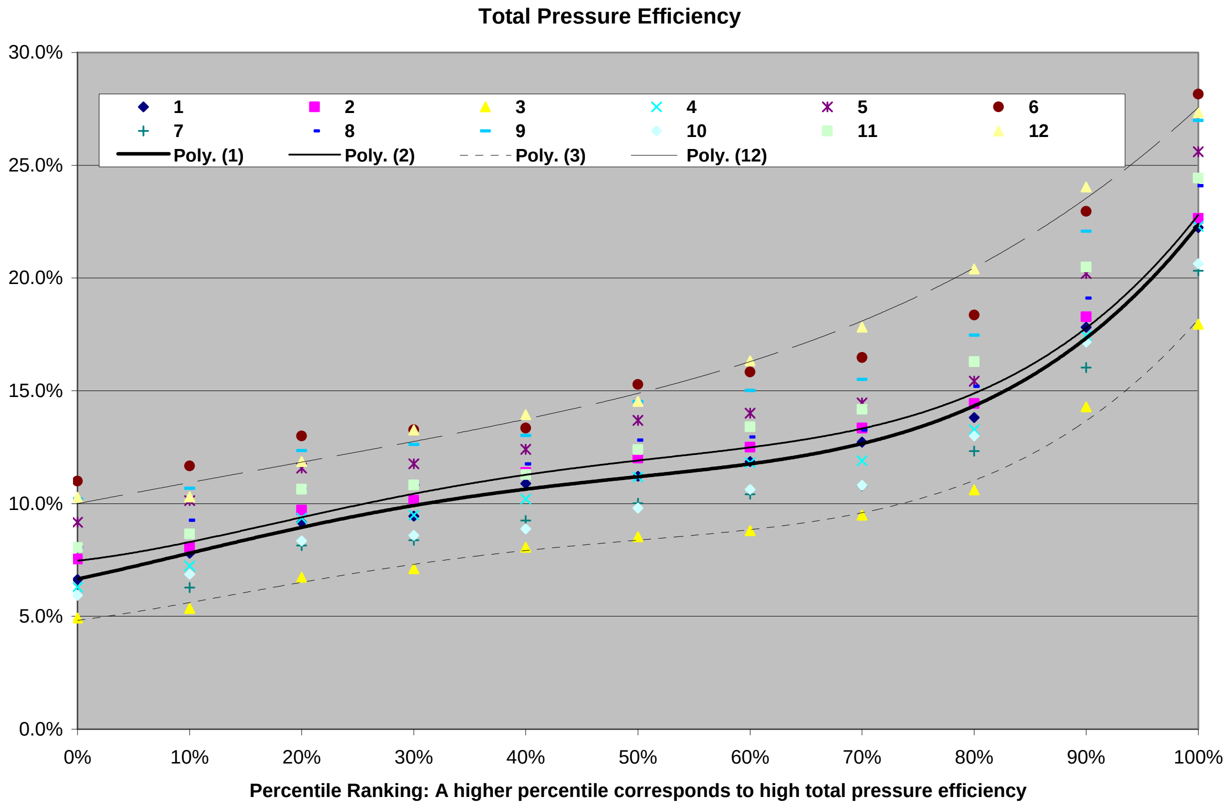

Figure 9 Percentile ranking of total pressure efficiency at selected operating conditions

Table 3 shows additional details about the percentile ranking curves in Figure 9. The table illustrates the equations and fitted significance for polynomial regression of total pressure efficiency based upon percentile ranking under four selected operating conditions in this study, i.e., conditions 1, 2, 3, and 12. Within each operating conditions range, average total pressure efficiency increased as a function of the ranking percentile.

Table 3 Polynomial regression of total pressure efficiency

Selected Operable Conditions	Polynomial Equation Y: Total pressure efficiency; X: Percentile	R-Square
1 (50-150Pa, 9.1-22.7m^3/min)	$y = 0.5166x^4 - 0.6121x^3 + 0.1467x^2 + 0.1058x + 0.0665$	0.9958
2 (75-125Pa, 9.1-22.7m^3/min)	$y = 0.6482x^4 - 0.9104x^3 + 0.3602x^2 + 0.0553x + 0.0747$	0.9962
3 (50-75Pa, 11.3-18.1m^3/min)	$y = 0.5081x^4 - 0.6526x^3 + 0.2145x^2 + 0.0635x + 0.0482$	0.9945
12 (125Pa, 14.7m^3/min)	$y = 0.1002x^4 + 0.0002x^3 - 0.0199x^2 + 0.0951x + 0.1$	0.9959

Based upon this percentile-ranking function, we may initially examine the difference in efficiency levels and the significance. In particular, we examined the significance of difference of average total pressure efficiency among all selected ranges of operating conditions given the same percentile. We then select a likely threshold of acceptance or qualification. Using this threshold of acceptance or qualification as a criterion, we then can identify FFU candidates of which total pressure efficiency is higher than the acceptance criteria.

In order to evaluate the significance of difference in efficiency levels, a series of ANOVA -and t-Tests were performed to test the statistical significance of difference in efficiency levels among the prescribed performance ranking and between operating conditions. Through performing ANOVA analyses for the ranking output across different operating conditions and ranges of the conditions as selected and shown in Table 1, we have found that there are generally significant differences in the average total pressure efficiency across and within the 12 selected conditions. For example, the difference in average total pressure efficiency at various operating conditions was statistically significant, as exhibited in Table 4.

Table 4. ANOVA significance of difference in total pressure efficiency at various conditions

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
3	11	1.018576	0.092598	0.001501
4	11	1.304881	0.118626	0.002092
5	11	1.58433	0.14403	0.002252
6	11	1.793494	0.163045	0.002686
7	11	1.178764	0.10716	0.001804
8	11	1.479902	0.134537	0.002131
9	11	1.704436	0.154949	0.002558

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.043761	6	0.007294	3.398084	0.00533	2.231192
Within Groups	0.150246	70	0.002146			
Total	0.194007	76				

Furthermore, a series of paired-sample t-Tests were performed to examine the significance of difference between average total pressure efficiency at different operating ranges. For example, a t-Test was performed for two different ranges of operating conditions: 1) pressure differential of 50-150 Pa with 9.1-22.7 m^3/min airflow rate and 2) pressure differential of 75-125 Pa with the same 9.1-22.7 m^3/min airflow rate. As shown in Table 5, we found that based upon the selected percentiles (0% up to 100%), the actual *p*-value of the t-Test indicates that there was a significant difference in average efficiency due to the difference between two operating-condition ranges. This significant difference in total pressure efficiency holds true even though the operation-condition ranges, i.e., conditions 1 and 2, had overlapped significantly.

Table 5. Significance of difference in total pressure efficiency

t-Test: Paired Two Sample for Means

	50-150	*75-125*
Mean	0.121463	0.127337
Variance	0.002049	0.001995
Observations	11	11
Pearson Correlation	0.999285	
Hypothesized Mean Difference	0	
df	10	
t Stat	-10.79656	
P(T<=t) one-tail	3.92E-07	
t Critical one-tail	1.812461	
P(T<=t) two-tail	7.84E-07	
t Critical two-tail	2.228139	

Through performing ANOVA- and t-Tests and examining the results, we discovered that there is significant difference in efficiency levels of various units and across operating conditions. In addition, no single set of operating condition or range of such operating conditions should be expected to represent any “typical” operation or efficiency levels., .

In fact, there are a variety of designs and possible ranges of operating conditions for FFU applications in cleanrooms and controlled environments. The levels of energy efficiency of an individual FFU may be quantified through performing laboratory tests and mathematical derivations. However, it appears that no single efficiency level can be used for baseline information, unless the designer or user has selected or required a specific operating condition for its cleanroom application.

5.6.1.3 Relative ranking system

In order to develop energy-rebate criteria, an alternative solution is needed. The following analysis presents an alternative to obtain energy-rebate criteria.

Based upon the percentile-ranking models developed from the test data, we established a relative ranking system among the sample FFUs. Relative ranking scores for all sample units, defined as the actual total pressure efficiency divided by the median value of the array of samples’ efficiency values under the same operating condition, were calculated.

Assigning a relative ranking score to each fan-filter unit, this relative ranking system allows identifying better performers vs. worse performers in terms of their total pressure efficiency levels. After identifying individual units that are relatively better performer under various operating conditions, the next step is to check and validate whether the relative ranking holds the same pattern even though actual efficiency levels have varied from unit to unit and from one operating condition to another condition. If the observed relative ranking pattern exhibits consistency, then using the raking system to filter out better performers vs. worse performers would become a valid approach that can be used to define acceptance criteria for rebate. For example, it can be used to identify units of which total pressure efficiency surpasses the acceptance criteria to be selected and defined as the minimum ranking requirement.

Table 6 Performance ranking scores for each unit under two different operating conditions

Operating conditions	1	2		Operating conditions	3	4	5	6	7	8	9	
Pressure (Pa)	50-150	75-125		Pressure (Pa)	50-75	75-100	100-125	125-150	75	100	125	
Airflow rate (m^3/min)	9.1-22.7	9.1-22.7		Airflow rate (m^3/min)	11.3-18.1	11.3-18.1	11.3-18.1	11.3-18.1	11.3-18.1	11.3-18.1	11.3-18.1	
Fan-filter unit	Relative ranking	Relative ranking	Unit - Accepted or Rejected	Fan-filter unit	Relative ranking	Relative ranking	Relative ranking	Relative ranking	Relative ranking	Relative ranking	Relative ranking	Unit - Accepted or Rejected
1	1.98	1.89	A	1	2.10	1.99	1.87	1.84	2.03	1.88	1.86	A
2	1.73	1.65	A	2	1.84	1.72	1.60	1.56	1.76	1.61	1.58	A
3	1.45	1.40	A	3	1.51	1.40	1.29	1.26	1.44	1.31	1.27	A
4	1.23	1.17	A	4	1.11	1.07	1.03	1.03	1.08	1.02	1.03	A
5	1.16	1.20	A	5	1.24	1.19	1.09		1.23	1.16		A
6	1.11	1.05	A	6	1.12	1.06	1.00	1.00	1.07	1.00	1.00	A
7	1.06	1.03	A	7	1.03	1.06	1.06	1.11	1.04	1.04	1.10	A
8	1.02	1.04	R	8	0.99	0.97	0.93		0.98	0.95		R
9	0.98	0.97	R	9	1.01	1.03	1.02	1.05	1.02	1.00	1.05	R
10	0.97	0.95	R	10	0.94	0.91	0.87	0.87	0.92	0.87	0.87	R
11	0.85	0.83	R	11	0.83	0.85	0.85	0.87	0.84	0.84	0.86	R
12	0.83	0.85	R	12	0.79	0.84	0.86	0.87	0.81	0.84	0.90	R
13	0.82	0.81	R	13	0.83	0.84	0.83	0.84	0.84	0.82	0.84	R
14	0.70	0.68	R	14	0.65	0.67	0.68	0.72	0.65	0.66	0.70	R
15	0.69	0.67	R	15	0.58	0.63	0.67	0.74	0.59	0.63	0.71	R
16	0.59	0.63	R	16	0.61	0.56			0.60			R
17	-	-	R	17		-	-	-	-	-	-	R

Table 6 shows the calculated relative ranking scores for each sample unit under nine different operating conditions, respectively. These nine operating conditions are conditions 1 through 9 as illustrated in Table 1. Relative ranking score was calculated as the ratio of actual total pressure efficiency of the unit to the median value of total pressure efficiency derived from the 17 sample FFUs corresponding to an operating condition.

For a selected operating condition or a selected range of operating conditions as illustrated in Table 6, units with relative ranking scores greater than 1.00 are identified as better performers.

For example, units 1 through 8 were identified as better performers under conditions 1 and 2; and units 1 through 7 and unit 9 were identified as better performer under conditions 3 through 9. In this pool of 17 samples, there are additional units such as units 8, 9, 10 having relative ranking scores near 1.00. Therefore, their acceptance for rebate was more susceptible to the exact cut-off point of the relative ranking scores. For instance, unit 8 would be accepted in conditions 1 and 2, while it will have to be replaced by unit 9 in conditions 3 through 9. Nonetheless, this could be due to relatively small sample size of the FFUs tested or just the fact that quite a few FFUs had relative ranking scores clustered within the vicinity of 1.00.

Using relative ranking scores as acceptance criteria for rebate would become very straightforward because this allows identifying energy-efficient products or models. The criteria can be developed based upon standard laboratory test results and the relative raking system. The qualified products (accepted samples) will be expected to perform at an efficiency level better than or close to median efficiency at a given operable condition and the same range of such conditions. For example, we can safely identify seven units (number 1 through 7 in Table 6) with relative ranking scores over 1.00, and recommend them be initially accepted for energy rebate program. In this case, fewer than half of the units (seven out of 17) tested would be initially accepted as candidates in energy-rebate program. As an alternative, if more units are desired for inclusion for rebate qualification, e.g., units 1 through 10. The expanded set of units (including 8, 9, and 10) were added because their performance was close to average and exhibited sufficient consistency under all the operating conditions listed in Table 6.

In either case, the caveat is that not all units accepted for rebate will be able to operate at all operating ranges. For example, units 5 and 8 will never operate at conditions 6 or 9. Users of this information or criteria recommendation should bear in mind that although unit 5 is made legible for meeting energy-rebate criteria in most of the cases, it might not be an appropriate candidate for the user to purchase, let alone to receive rebate. The bottom line is that unit 5 or 8 should not be selected by the end-user or the designer if the designed cleanrooms are expected to operate at conditions 6 and 9, thereby neither should it be qualified for rebate in this case.

5.6.2 Performance-based approach

As an alternative to statistical approach, a rebate may be awarded on the deemed-saving basis. The performance-based program will be based on certain quantifiable performance, e.g., how much better than average FFU, considering the actual price difference between more efficient and less efficient units. Cleanroom users can earn incentives for using energy efficient units. For example, designers, owners of the facility, and/or utility companies can select certain operating condition and calculate the actual power demand and annual energy consumption of FFUs tested. By examining the potential utility savings from efficient FFUs and the price differential between efficient units and less-efficient unit, the utility companies may wish to customize the energy rebate on a case-by-case basis. For example, they will then decide whether to award any financial incentive rebate to certain products, and the magnitude of such incentive rebate. The reported performance data and the equations will assist them to identify functional and efficient units, and will provide the base for quantify the magnitude of rebates considering their own budget, deemed saving potential, and the price differential of FFUs.

5.6.3 Recommending criteria options for energy incentive programs

In order to define the criteria used for utility's rebate program, we recommend two options to formulate energy incentives: prescription- and performance-based incentive programs.

5.6.3.1 Criteria for prescription-based incentive program

The criteria of prescription-based program can be established by specifying a set of products that meet or surpass certain threshold of energy performance. Such threshold can be identified and selected based upon relative ranking scores of the FFU energy performance. Analyses were conducted to determine the set of FFUs that would outperform others, e.g., approximately half (or more) of the rest of sample units. Our tests, analyses, and validations show that most of the units with a relative ranking score greater than 1.00 under one of the operating conditions largely exhibited a relative ranking score greater than 1.00 under the other operating conditions listed in the table. Except for some operating conditions that a unit may not achieve under any circumstances, the relative ranking scores of the sample units in this project have exhibited consistent patterns in relative performance compared to a median performer. Therefore, using the relative ranking score is suitable for identifying FFU out-performers in terms of energy efficiency. Based on the statistical analyses, we recommend the following guidelines for utility companies to consider in formulating a prescription-based energy-rebate program:

1) The rebate-criteria for prescription-based incentive program will be the relative ranking scores of the FFU products gathered from the sample units tested.

2) Identify an initial set of higher performers of energy-efficient fan-filter units from the 17 sample units in this study, and reward dollar rebates for procuring these products that surpass the minimum energy-rebate criteria, e.g., relative ranking scores greater than 1.00, or seven out of 17 products tested. The utility companies, at their own discretion and preference, may wish to consider more or less stringent criteria based upon percentile higher or lower than 50%, e.g., 10 out of 17 products tested. In either case, higher-performers (i.e., higher energy-efficiency) in the FFU sample pools may be identified as initial set of candidates qualified for a specific rebate.

3) Identify additional high-performers of energy-efficient units to be included in the rebate program, through requesting and obtaining comparable and standard test results of additional units in the market. Additional units may be tested and evaluated. Such new units may include additional 61-cm by 122-cm (2-ft by 4-ft) units and 122-cm-by-122-cm (4-ft-by-4-ft) units. A quick way to evaluate whether or not a new unit is qualified for rebate is to compare itself with the existing relative ranking system developed from the 17 sample units. As an alternative, especially if there are substantially more units and products tested, a new relative

ranking system would need to be developed using the method presented in this study. Then newer rebate criteria may be established and used for future rebate programs.

4) As more units are tested using the standard laboratory tests, compatible performance data are available for further analyses. Newer rebate criteria may then become necessary over time and can be developed using the statistical method in the study. A periodic update of the list of product qualified for rebates may then be made available for users and utility companies in the future. This new information and dynamic criteria will not only reward the use and purchase of energy-efficient units on the market, but also will encourage suppliers to design, develop, and market more efficient units that would ultimately transform the FFU market toward higher energy efficiency.

5.6.3.2 Criteria for performance-based incentive program

The criteria of performance-based program can be established by calculating energy savings from FFU products for a specific cleanroom application, while taking into utility costs (e.g., electricity charge rate) and actual unit cost differential among the FFU products. The estimates of energy savings will be made based upon the test results applicable to a specific set of design or operating conditions of the FFU for cleanroom applications.

This option of energy rebates will be awarded on the case-by-case basis, considering units' functionality, deemed energy-savings under designed conditions, and the unit cost. For example, designers, owners of the facility, and/or utility companies can agree upon and select a certain operating condition, and calculate the actual power demand and annual energy consumption of available FFUs as compared to the sample FFUs.

By examining the potential cost reduction in energy and power demand from more efficient FFUs and the price differential between efficient units and less-efficient units, the utility companies may customize the energy rebate on a case-by-case basis. Based on the calculation(s), the utility companies can first decide whether to award any financial incentive (rebate) to any products based upon the magnitude of the potential energy and power demand benefits and payback. If it is determined to be appropriate to award an incentive, they will need to specify the magnitude(s) of such incentive rebate and/or a formula to recommend and quantify the magnitudes. The decisions should take into consideration of actual functionality of FFUs under designed operation conditions, potential energy savings, and product price.

The reported performance data, operable conditions, and the equations developed for individual products from laboratory testing in this report will be used to assist in identifying functional and efficient units for specific applications. This will provide the base for quantifying the magnitudes of rebates, considering their own budget, deemed saving potential, and the price differential of individual FFUs.

The LBNL standard has been and is being adopted by users and owners to understand FFU performance. The results are used in their process of selecting and purchasing fan-filter units with better and improved performance. In addition, the outcomes of the standard tests are now being considered by utilities seeking to promote applications of energy efficient FFUs. A successful energy-rebate program would allow a utility to provide financial incentive for end-users to specify and purchase energy-efficient fan-filter units. Furthermore, some end-users have been proactively pursuing ways to reduce cleanroom operating costs and life-cycle costs by selecting energy-efficient fan-filter units. For example, in designing and constructing large cleanrooms, some large companies in the US and Asia including Texas Instruments have required FFU suppliers or bidders to perform and report tests according to the LBNL standard, which allows provision and comparison of performance data in a consistent way.[2][3]

6. Summary

All individual standard laboratory-testing reports have been completed and reported back to anonymous individual participants in this project. Each report on an individual fan filter unit provides rigorous and useful data produced from standard characterization of FFU's operation. In the course of the project, the laboratory method previously developed at LBNL has been under continuous evaluation and update.[2][3] Based upon the updated standard, it becomes feasible and easier for users and suppliers to characterize and evaluate energy performance of FFUs in a consistent way.

Laboratory testing of FFU energy performance has provided useful data for suppliers and end users to understand the functionality and performance of FFU products under a variety of operating conditions. More importantly, suppliers and users can now quantify and compare energy performance of FFU products under any pre-determined and operable conditions. For the design and construction of large cleanrooms, some companies have required FFU suppliers to report laboratory tests based upon the characterization methods developed at LBNL[2][3]. For example, many manufacturers of fan filter units expect to produce or obtain such data to quantify energy efficiency levels of their products. Ultimately, the standard test method is expected to be used or adopted by more and more suppliers, specifiers, and end-users to understand and improve FFU functionality and performance, as well as utilities seeking to promote applications of energy efficient FFUs.

In this demonstration project, we have refined the characterization methods, performed laboratory experiments to characterize fan-filter units, developed polynomial regression models to quantify the efficiency and power demand as a function of airflow and pressures. We have found significant variations in energy performance from unit to unit, as well as significant variation of units' performance across various operating conditions. The observed significant variations posed challenges in identifying a single efficiency level as baseline information for utility's rebate programs.

In addition, for the benefit of possible energy incentive programs operated by California utility companies, we have performed statistical analyses of the test data, developed a relative ranking system, and examined statistical consistency of observed variation in units' energy performance. Based upon the statistical evaluations of the test data gathered from testing the sample FFUs, we have developed an energy-rebate criteria, which allows identification of an initial set of units and products that are more energy efficient at a given operation condition or within a given range of operating conditions. Utility may use the information in formulating their energy-rebate programs to promote the use and purchase of FFUs that are more energy efficient.

In summary, we have accomplished the following:

- Designed, constructed, and commissioned a new test rig used to perform FFU testing and experiments.
- Developed and performed laboratory tests of 17 different FFUs.
- Produced and delivered 17 individual reports on characterizing dynamic operation of individual FFUs with various controls and operation.
- Developed laboratory experiments to examine, validate, and improve the laboratory test method including procedure that were used to characterize various FFUs.
- Refined the draft standard method previous developed at LBNL; promulgate the application of the new standard methods through interactions and communications with the industries (users, manufacturers, professional society, and magazines).
- Developed mathematical modeling of characterizing energy performance of individual fan-filter units within their operable conditions.
- Performed statistical analyses and developed a relative ranking system that resulted in initial criteria to compare units' performance.
- Developed options of criteria for energy-incentive program, identified higher-performers of energy efficient FFUs, and provided recommendations for utility companies in designing and implementing energy –rebate programs for promoting use of energy-efficient FFUs.

Through an extensive review of open literature, development of the standard methods, and additional experimental validations of the refined methods in this project, the following issues are identified to be important and may need future development.

- Continue to improve rigor and robustness of the new, largely improved standard methods, e.g., characterize design and speed-control impacts on overall performance, e.g., type of motors, internal housing, air path, and size of units.

- Characterize internal pressure distribution, e.g., pressure variations across HEPA/ULPA filters, and within the air-path of the FFU.

- Characterize airflow uniformity.

While the contamination control industries are moving toward tighter contamination control and increasing desire for higher energy efficiency, it is important to strategize the development and implementation of higher-efficiency FFUs in actual cleanrooms. The following includes important actions that need to be taken:

- Disseminate the results among technical and professional societies and across industries.

- Interact with relevant professional societies and standard development bodies to further absorb and adopt the refined standard test method, e.g., assist and facilitate the development and publication of industrial standard - IEST RP036.1: Testing Fan Filter Unit.

- Provide technical assistance to users and manufacturers to use efficient FFUs and improve FFU performance.

- Assist utilities to establish and implement energy-rebate program to promote FFUs that outperform others.

Identifying and selecting energy efficient units in cleanroom applications can bring about energy and demand savings while maintaining and improving the effectiveness of contamination control. Through this research and demonstration project, it becomes feasible for end users or cleanroom owners to become better informed of the energy performance to aid in their planning and selection for use in new facility construction or renovation. For example, they may now require suppliers to provide the units' performance obtained through the LBNL standard. In addition, more FFU manufacturers are becoming motivated to understand performance of their units, to improve design, operation and controls of their FFUs, and to serve their customers better. Furthermore, utility companies or other public interest programs may use the results and recommendations to establish energy-rebate criteria, and implement programs to encourage the use of efficient units. Last but not the least, the outcomes from this work have and will continue to facilitate and add to the on-going development of an industrial standard, i.e., IEST- RP-CC036.1: Testing Fan Filter Unit.

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[12] ASHRAE. 1999. *ANSI/ASHRAE Standard 51-1999*. Also AMCA 210-99. Laboratory Methods of Testing Fans for Rating.

[13] ASHRAE Standard 41.2: Standard Methods for Laboratory Airflow Measurements

[14] ASHRAE Standard 37: Methods of Testing for Rating Unitary Air Conditioning and Heat Pump Equipment

[15] International Organization for Standardization (ISO). 2003. ISO 5167. "Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full." Part 1: General principles and requirements; Part 2: Orifice plates; Part 3: Nozzles and Venturi nozzles; Part 4: Venturi tubes."

9. Appendices

9.1 Initial Test Setup

It is essential to obtain accurate measurements of total electric power demand, airflow rates (or actual airflow speeds), and the static (and total) pressure differential across the FFU. Among these, accuracy and complexity in airflow rate, power demand, and pressures, and locations of pressure measurement applicable to FFU are important considerations in test rig setup and equipment selection.

To determine the initial dimensions of the test duct section, we referred to previous work and a number of ASHRAE Standards on airflow and pressure measurements. For example, ASHRAE Standard 51 (i.e., ANSI/AMCA 210): Laboratory Methods for Testing Fans for Aerodynamic Performance Rating provides guidance that specifies a minimal duct length of 10 times of hydraulic diameter [12]. According to this, the ductwork leading to a 61-cm by 122-cm (2-ft by 4-ft) FFU section would require a minimal length of 8-m (27-ft). As an alternative, it is possible if the duct section were to be reduced to a smaller size in order to reduce its minimal length. In the latter case, however, the required length of transition piece would still be equally significant if not longer because the tapering angle is required to be no greater than 7½° (degree).

In addition, some other standards provide different requirements for measurement locations of the external pressures[13][14][15]. For example, one ASHRAE standard specifies test duct section with the same sectional dimensions of the unit being tested, with a duct length no less than 2½ times the square root of the product of the duct dimensions [13]. For a 61-cm by 122-cm (or 2-ft by 4-ft) duct section, the minimal duct length would then be about 2.2-m (7-ft). The pressure taps are located at 4/5th of the duct length away from the tested unit, which is 1.7-m (5.7-ft). It also requires a downstream duct straightener for the flow meter, with a length of five to five and a quarter times the diameter of the cross-section circular duct.

Figure 11 illustrates the initial experimental layout for measuring airflow rate, static (and total) pressure, and total electric power demand. The unit's airflow rate, airflow speed, total electric power demand was concurrently recorded for all operating points adjusted by varying the pressure differential and airflow rate across the FFU. The airflow path was designed as a flow-through to FFU in the test rig. This conceptual setup shows that flow-nozzle(s) are used to measure airflow rate in the upstream of airflow path directed toward the FFU inlet. In this project, the FFU face was installed to be vertical. Airflow from immediate downstream of the FFU was discharged to the atmosphere. Airflow rate measurement contains a single-nozzle for recording airflow rates through the tested unit. Figure 10 shows the actual test rig setup at LBNL.

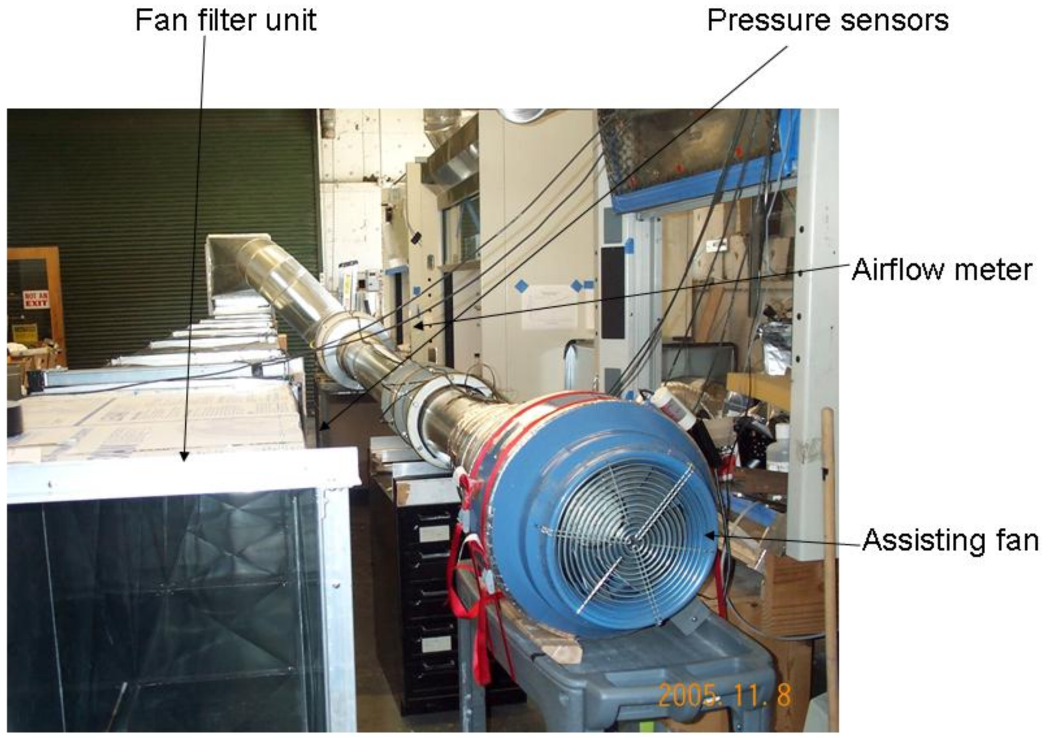

Figure 10. Laboratory test rig at LBNL

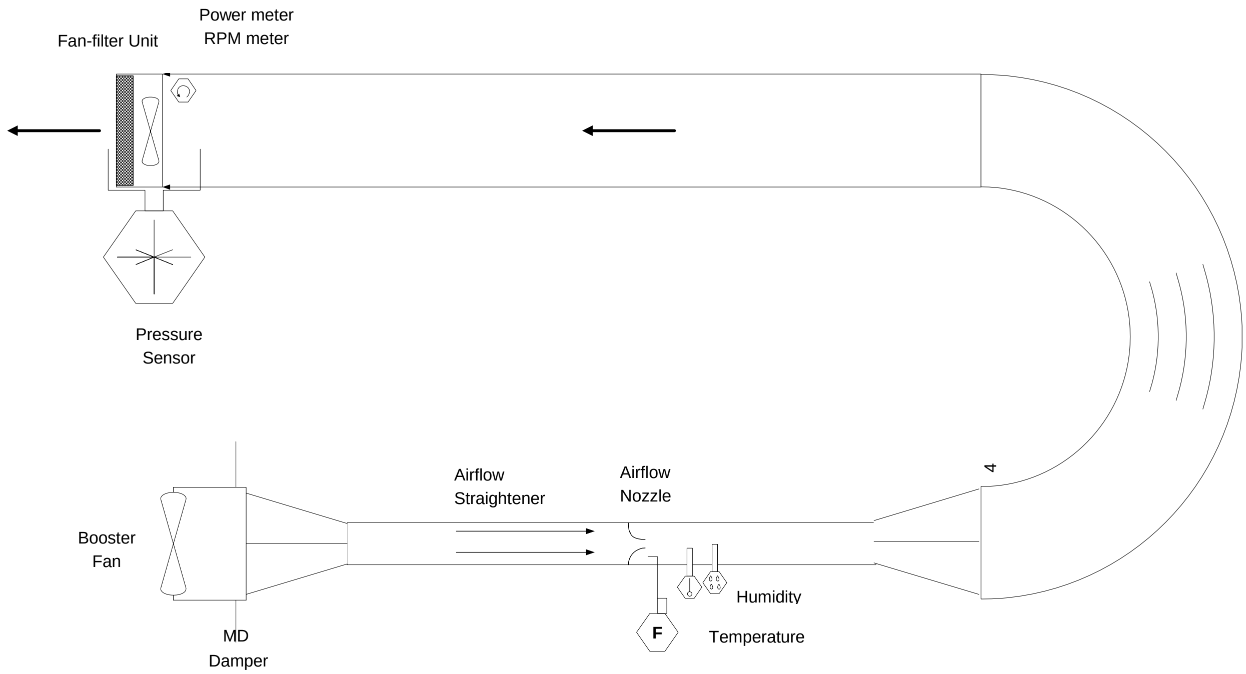

Figure 11 FFU test setup

Rigid metal ductwork chamber was built and installed for the test rig. The FFU tested was mounted vertically on the exit end of a straight duct. The size of ductwork connected to the FFU was 61-cm by 122-cm (or 2-ft by 4-ft), approximately equal to the FFU section. The length of straight duct upstream of FFU was 10-m (33-ft), which was approximately 12 times of the hydraulic diameter of the ductwork connecting to the unit.

Along the duct there are three pressure taps installed using Pitot Tube to monitor the pressure difference between the selected locations inside the ductwork and where the air is discharged from the unit (outside of the duct). The measurement points of the Pitot Tubes were located at the center of four duct sections, with a distance of 0.3-m, 2.6-m, 4.9-m, 8.7-m (1-ft, 8.5-ft, 16-ft, and 29-ft) away from the FFU airflow inlet. Exit airflow from the downstream of the FFU was directed to the atmosphere from the filter face. The pressure taps were installed at the following distance away from the inlet of test FFU: 0.3-m(1-ft), 2.6-m (9-ft), 4.9-m (16-ft), and 8.7-m (29-ft).

Recommended by the flow-nozzle manufacturer, there was a recommendation of minimal duct length for airflow uniformity in flow nozzle. We however initially installed a 5-ft duct straight round duct with a diameter of 10” upstream of the flow meter, and an 8-ft duct straight round duct with a diameter of 10” downstream of the flow meter.

The initial test rig setup contained a combination of conservative requirements by existing ASHRAE/AMCA standards, and was used to evaluate the sample FFUs in this study.

9.2 Test Equipment and Device

In the tests for 61-cm by 122-cm (2-foot by 4-foot) fan filter units, we used a nozzle-based airflow meter to measure airflow rates ranging from 250 to 1300 cfm (7 to 37 m^3min^{-1}), corresponding to pressure signals ranging from 15 to 413 Pa with rated accuracies of 0.5 % of the reading. The airflow rate accuracy would be within 5% even when the pressure measurement error approaches one Pascal or slightly higher. Specifically, a nozzle Pitot airflow sensor was used.[1] It combines integral flow straightener, a flow nozzle and a Pitot averaging array to minimize the effects of turbulence, vortexing, swirl and profile shift. The flow straightener help align the flow and the nozzle conforms the airflow to a known profile shape. The Pitot averaging array installed at the throat of nozzle measured the conditioned velocity profile, the nozzle eliminates distortions in the velocity profile caused by upstream obstructions and doubles the velocity before it is measured by the Pitot averaging array, requiring no upstream straight run with ±0.5% reading accuracy.

An eight-channel electronic data logger was used to record measured parameters including airflow rate, air pressure, temperature, humidity, electric power demand, and fan-wheel speed for each of the testing conditions. Specifically, we used Energy Conservatory Model APT 8.[2] The output signals of data logger including pressure transducers were recorded with a computer-based data acquisition system. The eight-channel electronic differential pressure transducer has a measuring range of ± 400 Pa, with rated accuracies of the larger of ± 0.2 Pa or ±1% of reading. The calibration of the eight-channel pressure transducer system was checked using a micro-manometer that has a micrometer and electrical circuit for precisely measuring the height of the fluid column.

Additional pressure transducers were used to measure and monitor air pressures in various locations in the test rig. Pitot tubes were used to measure and record pressure differential before and after of the fan-filter unit. Pitot tubes were installed at various locations in the ductwork or

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[1] http://www.thermo.com/com/cda/product/detail/0,1055,14801,00.html; Model NZP1031-10”-1-CF (circular carbon steel, standard flange and duct section, neoprene gaskets; 10-inch aluminum nozzle with 316 stainless steel probe array, aluminum flow straightener; Brandt standard flanges with industry standard bolt hole pattern with a companion flange.

[2] http://www.energyconservatory.com/products/products3.htm

chamber to measure or monitor of pressure changes along the ductwork or chamber leading to the fan-filter unit. Four such static pressure taps were installed at locations of 0.3-m (1-foot), 2.6-m (8.5-foot), 4.9-m (16-foot), 8.7-m (28.5-foot) away from the inlet of an FFU connected at the end the 10-m (33-ft) ductwork.

The fan-wheel speeds of the FFU were recorded using a device for recording number of rotations per minute (RPM) concurrently with other measurements for each of the test conditions. An RPM sensor[3] was installed at a fixed location upstream of the FFU inlet. The front-panel programmable RPM sensor (ACT-3) has an RS232 bi-directional interface. It includes NIST Traceable Certificate of Calibration, measuring 5 RPM - 999,999 RPM, with one or multiple pulses per revolution and scaling from 0.0001 to 99,999, totalizing and counting from 1 to 99,999. It has two alarm set points, latching or non-latching, with programmable hysteresis, low limit lockout, and analog voltage output of 0-5 Vdc with current output of 4-20 mA. The location was selected to allow direct monitoring of the speed of rotating fan-wheel blades. For various fan-filter units, additional painting on their fan-wheel blades, along with necessary accessories such as reflective tape, was necessary to enable proper sensing and recording of fan-wheel speeds.

A portable barometer[4] with digital display was used to record the atmospheric pressure around the test rig. The barometer has accurate pressure sensing with microprocessor-based computations to provide instantaneous pressure readings. The barometer has an accuracy within ± 0.02% F.S. (F.S. = 900 mm Hg abs, or 120 kPa). The device is temperature compensated over its operating temperature range. Sensors used to record the atmospheric pressure, air temperature and humidity were placed at locations within the laboratory that represent the psychometric conditions of the air flowing in and out of the test rig.

The total true mean electric power demand for the whole unit included fan motor, speed control and display device, transformer, and additional accessories. Total electric power demand was measured using an accurate electric power meter for one-phase AC power. It measured true power ranging from 0 to 500 W with an accuracy of the larger of ±0.2% of reading and ±0.04% of the full scale.[5] For example, the accuracy of the power meter measuring power demand of 100

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[3] http://www.monarchinstrument.com/act.htm#Model%20ACT-3

[4] http://www.novalynx.com/230-355.html

[5] http://www.ohiosemitronics.com/products/gw5.html; http://www.ohiosemitronics.com/pdf/gw5.pdf;

W and 300 W would be ±0.2 W and ±0.6 W, respectively. We calibrated the actual electric power demand readings against a highly accurate power meter with ±0.05% basic accuracy.[6] It was accurate with distorted waveforms and poor power factors and had a built-in integrator for measuring energy maximum demand or averaged values. The maximal reading deviation of the power meter used in FFU testing from that of the highly accurate meter was within 2%.

In order to control the airflow rate and pressure differential across the FFU tested, we used an ancillary booster fan[7] and a damper[8] to modulate static (and total) pressures and airflows across the FFU. The airflow rates under a certain fan-wheel speed setting were adjusted by two means: 1) varying fan-wheel speeds of the booster fan thereby changing airflow rates, and 2) controlling the pressure across the airflow damper of which the position affects the pressure loss as a way to emulate the changing pressure resistance in the external system. The booster fan is used to emulate various external resistances against which the unit may be able to overcome. The booster fan included a variable-speed controller for use of adjusting the airflow rates. Details of selecting operating conditions and the testing procedures are described in the standard test method for FFUs with different speed control techniques: 1) FFU with a single-speed-drive motor, 2) FFU with a multi-speed-drive motor, and 3) FFU with a variable-speed-drive (VSD) motor.

9.3 Leakage Detection and Quantification

The equipment setup and test rig configuration was expected to ensure minimal air leaks between the enclosed ductwork/chamber and its surrounding environment - the ambient environment external to test rig. The leakage should be maintained at a minimal level or accurately quantified so that airflow rate through the FFU can be accurately quantified.

The air leakage was first quantified and evaluated by performing the following 1) sealing the test rig (including FFU), 2) connecting a low-flow flow meter coupled with Pitot tube, 3) measuring leaking airflow rates corresponding to various air pressure differential across the ductwork.

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[6] http://www.atecorp.com/Equipment/Voltech/PM3000A.htm; Voltech Universal Power Analyzer (PM3000A).

[7] http://www.kbelectronics.com/catalog_fan_oem_wall.htm; Kanalflakt Fan. KBWC-115, 115 VAC 50/60 Hz Rated 15.0 amps.

[8] http://www.continentalfan.com;

The measured airflow rate corresponding to certain pressure differential was used to quantify airflow leakage ratio, defined as leaking airflow rate divided by the total airflow rate at the pressure inside the ductwork of the test rig. Measures to reduce leakage of test rig were then carried out to minimize leakage ratio for tested operating conditions.

Specifically, the leaking airflow rate was measured using a differential-pressure Venturi-type flow meter. The Venturi-type flow meter is a Style VS brass-screwed meter with a diameter of 3.8-cm (1.5-inch) and a length of 10.8-cm (4.25-inch) with an accuracy of ±1%[9]. With a fan-filter unit attached and tested, we detected air leakage in the ductwork of the initial test rig that was constructed. The ductwork including all traverse joints, longitudinal seams, and duct wall penetrations created for wire or cable connections was then manually sealed using sealant.

Additional leakage tests and sealing were performed accordingly to quantify the leakage levels. After some iteration, we reduced the maximal air leakage ratio well within 3% when the airflow rate was 8.5 m^3/min (300 cfm) while the pressure across the ductwork of the test rig was 140 Pa (0.56-inch water). In principle, leaking airflow rates of the ductwork were quantified by the following equation.

Where $Q_{ductleak}$ is the duct leakage rate (cfm or m^3/s), C is the constant reflecting area characteristics of leakage path; ΔP_s is the static pressure differential between interior and exterior of the ductwork; and N is the exponent relating to turbulent or laminar flow in leakage path . Actual leakage ratio became much lower than the measured 3% when the airflow rates through the unit were higher than 8.5 m^3/min (300 cfm), while the pressure across the ductwork was maintained the same or even lowered. For example, the leakage ratio of the test rig became 1.5% down to 1% when the actual airflow rate was set at 17 m^3/min (600 cfm) while the pressure across the ductwork of the test rig was 140 Pa (0.56-inch water) or down to 70 Pa (0.28-inch water), respectively. On the other hand, the leakage ratio of the test rig became 2.2% when the actual airflow rate was set at 17 m^3/min (600 cfm) while the pressure across the ductwork of the test rig was set higher at 250 Pa (1.0-inch water). In the worse case scenario, the leakage ratio became 4.4% if the pressure differential increased to 250 Pa (1.0-inch water) while airflow rate was maintained at the level of 8.5 m^3/min (300 cfm).

Based upon the leakage quantification described above, we would be able to calculate the leakage airflow rates for each of the operating conditions and modify the actual airflows through the FFU tested. However, given that common airflow rates for a 61-cm by 122-cm (2-foot by 4-

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[9] http://www.gerandengineeringco.com/

foot) unit would be higher than 8.5 m^3/min (300 cfm), actual leakage airflow rates associated with the test rig would normally appear to be within 3% of the measured airflow rates. The air leakage was therefore considered negligible in this test rig because of the small deviation from actual airflow rate measured by the flow nozzle.

9.4 Test setup for evaluating repeatability

Prior to the study, we reviewed open literature including ISO Standards, AMCA and ASHRAE Standards that address the requirements for measuring airflow rate and air pressures associated with different equipment in ducted or un-ducted testing layouts.[12] [13][14][15].

These standards are either applicable to characterize fan performance, or specific device such as air conditioners or heat pumps in various laboratory setting. For example, the AMCA/ASHRAE standard requires large chambers and flow baffles to create uniform airflows entering the fans to be tested. However, none of these standards addresses any specific method applicable to characterize fan filter units or provides any direct guideline on an acceptable laboratory method to measure power demand, airflow rate, and pressure differential across the fan filter units.

In order to understand the potential influence of various setup, ambient conditions, and layout of the test rig on laboratory measurements, we designed and installed various test rigs to address potential implications of such variations on the repeatability of measured performance. We then designed a set of experiments and evaluated the significance of difference in measured results. In particular, the experiments were to evaluate consistency and repeatability of test results through characterizing the same units at different ambient conditions, at opposite airflow directions, and in test rigs with different sizes such as duct lengths. The following summarize the approach and results.

9.4.1 Repeatability of measured performance at different flow restrictions created by placement of an FFU in opposite directions

In order to evaluate the impacts of airflow restrictions at the inlet and outlet of an FFU on measured performance, we placed selected FFUs with HEPA/ULPA facing into the ductwork with a section size of 61-cm by 122-cm (2-ft by 4-ft). The FFU inlet was un-ducted and took air from the open ambient space through a prefilter. With this FFU setting, we performed experiments on airflow, pressure, and power demand, and compared the results with those from original test setup whereby ducted air was directed into the FFU inlets and flew through the HEPA/ULPA filter that faced open air.

The new test rig setup is illustrated in Figure 12. In this setup, the direction of the FFU tested, the flow meter, and the booster fan were all reversed compared to its original setup illustrated in Figure 11. In this test setup, the supplied airflows were free-flow before entering the FFU inlet while the airflows out of the HEAP/ULPA filter are restrictive by the sized ductwork, i.e., 61-cm by 122-cm (2-ft by 4-ft) ducted chamber. In this case, the airflow rates were measured downstream of the FFU outlet.

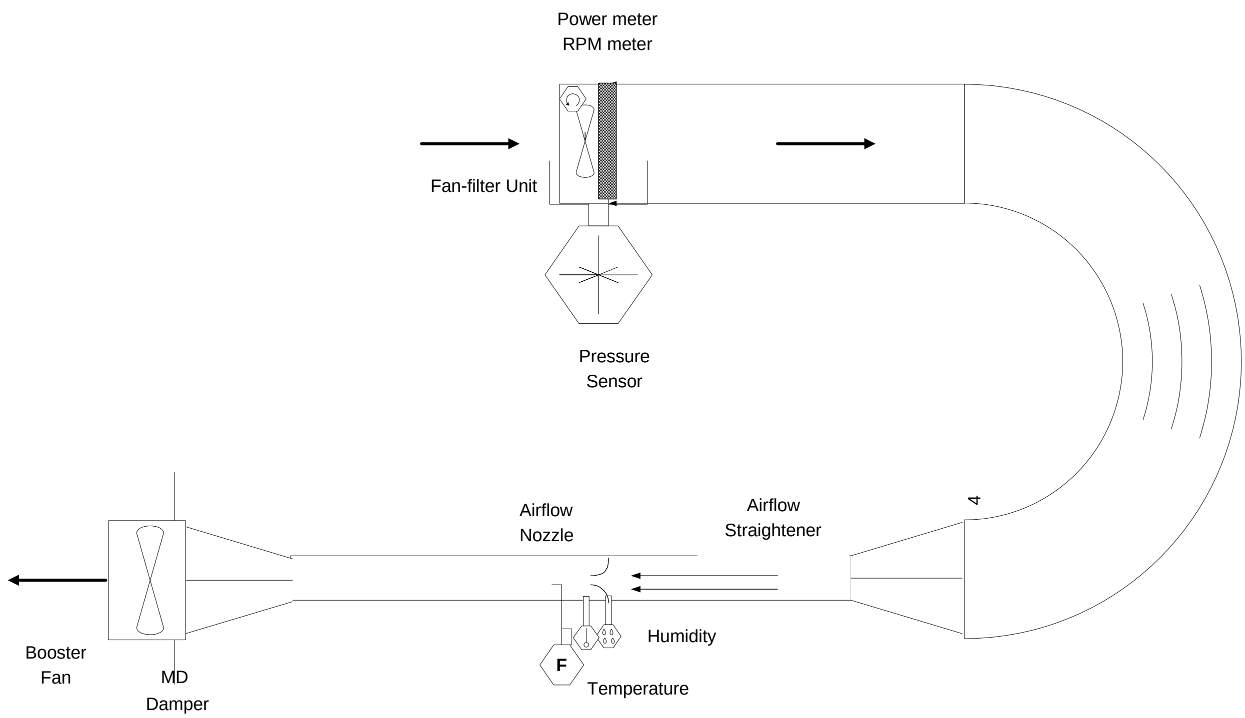


Figure 12 Test rig with varied airflow restrictions at FFU inlet and outlet

A comparison of the measured electric power demand of the two selected FFUs from both test rig setup (Figure 11 and Figure 12) shows that the relative difference of measured power demand was within 2% or less for each FFU sample between the two test-rigs. The relative difference in measured total pressure efficiency is even smaller, mostly within 1% at the operable conditions listed in Table 1 for each unit.

Based on the measured data and evaluations, we have found that the measured performance corresponding to two different flow restrictions at FFU inlet and outlet was repeatable between the two rigs, without inducing variance in uncertainties. The testing results show that while there were variations in airflow restrictions at the inlet and outlet of an FFU, placing an FFU with HEPA/ULPA facing into a restrictive, ducted chamber or to a non-restrictive, open space produced repeatable measurements of FFU airflow rates, pressures, and power demand for a same operating condition. The results in total electric power demand as well as total pressure efficiency were consistent, even though the regression equations differed from each other.

In summary, the influence of the flow directions and restrictions at FFU inlet and outlet on the measured electric power demand or total pressure efficiency appeared to be minimal and was negligible.

9.4.2 Repeatability of measured performance at different ambient conditions

One would expect that variations in motor temperatures might affect the actual efficiency or electric power demand of fan motors. If other parameters remain the same for the same FFU, ambient air temperatures might influence the steady-state motor temperature. Therefore, large difference in ambient temperatures might have some affect on operating motor efficiency.

In order to examine the hypothesis, we selected two FFUs and repeated measurements of energy performance of each unit at different ambient temperatures: the first unit was tested in a relatively warm day in summer where the inlet air temperature was 26°C and was tested again in the fall when it was cooler (21°C); the second unit was tested in a mild summer day when the inlet air temperature was 21°C while it was tested again in a cooler day where the inlet air temperature was 17°C.

For the first unit, we have identified slightly higher power demand for the unit when operating at warmer temperatures (26°C compared to 21°C). This was contrary to what would have been expected in that the fan motor would be more energy-efficient if at all under a warmer condition. However, the measured relative difference was within 3% for power demand (Watt) and was within 2% for the total pressure efficiency under two ambient air temperatures for the operable conditions listed in Table 1. The difference was within measurement uncertainties.

For the second unit, we have identified slightly higher power demand for the unit when operating at a cooler temperature (17°C compared to 21°C). This was in line with what would have been expected in that the fan motor would be less efficient when the motor was cooler. However, the measured relative difference was within 2% for power demand (Watt) and was within 2% for the total pressure efficiency under two ambient air temperatures for the operable conditions listed in Table 1. The difference was within measurement uncertainties.

While large difference in ambient air temperatures might somewhat cast initial influence on the actual power demand of the FFU motor, the experimental results showed insignificant influence of the recorded ambient air temperatures on measured power demand and actual total pressure efficiency measured from the experiments.

From the investigation and performance comparisons, we recommend that measures should be taken to ensure FFU testing be conducted under a relatively constant ambient temperature, which normally would call for warm-up time for the test rig and FFU to operate at a stable condition. In addition, we should avoid testing FFU at extreme air temperatures, and even better, maintain the ambient air temperature for the FFU test rig within a certain range, e.g., normal room temperatures.

9.4.3 Repeatability of measured performance measured with different lengths of the ductwork leading to an FFU

Various ASHRAE and AMCA Standards specify different requirements for duct lengths leading to tested units (air conditioner, coil, fan, etc.) for airflow rate and pressure measurements, but none of them addresses fan-filter units. The initial test rig setup in this study adopted perhaps a more conservative approach in terms of minimum duct length to be recommended. The initial straight ductwork was composed of eight 61-cm by 122-cm (2-ft by 4-ft) sections that were connected in sequence, each having a length of 60-cm (46-inch). This equaled to approximately 12 times of the duct's hydraulic diameter (32-inch).

In order to investigate the effect of lengths of the ductwork leading to FFU inlet or outlet on the measured performance of fan filter units, we reduced the length of the 61-cm by 122-cm (2-ft by 4-ft) ductwork by removing some of the sections, and conducted experiments respectively. The shortened duct lengths ranged from twelve- down to 1.5-times of duct's hydraulic diameter ($12D_h$ down to $1.5D_h$), respectively.

In all these experiments, we placed the selected FFUs with HEPA/ULPA facing into ducted chamber and recorded airflow rates, pressures, power demand. Figure 13 illustrates the test rig setup. In this test setup, airflows were free-flow before entering the FFU inlet while the airflows out of the HEAP/ULPA are restrictive, i.e., 61-cm by 122-cm (2-ft by 4-ft) ducted chamber. The airflow rates were measured downstream of the FFU outlet.

Based on the measured data and comparisons, we have found that the measured performance corresponding to different duct lengths was repeatable without inducing variance of accuracy concerns. The testing results show that while there are variations required duct lengths for different equipment suggested by some ASHRAE/AMCA standards, we found no significant difference in the measured energy performance of fan filter units from our study. The required ductwork length is found to be acceptable at 1.5 D_h level. The results in total electric power demand as well as total pressure efficiency are consistent, even the regression equations differed.

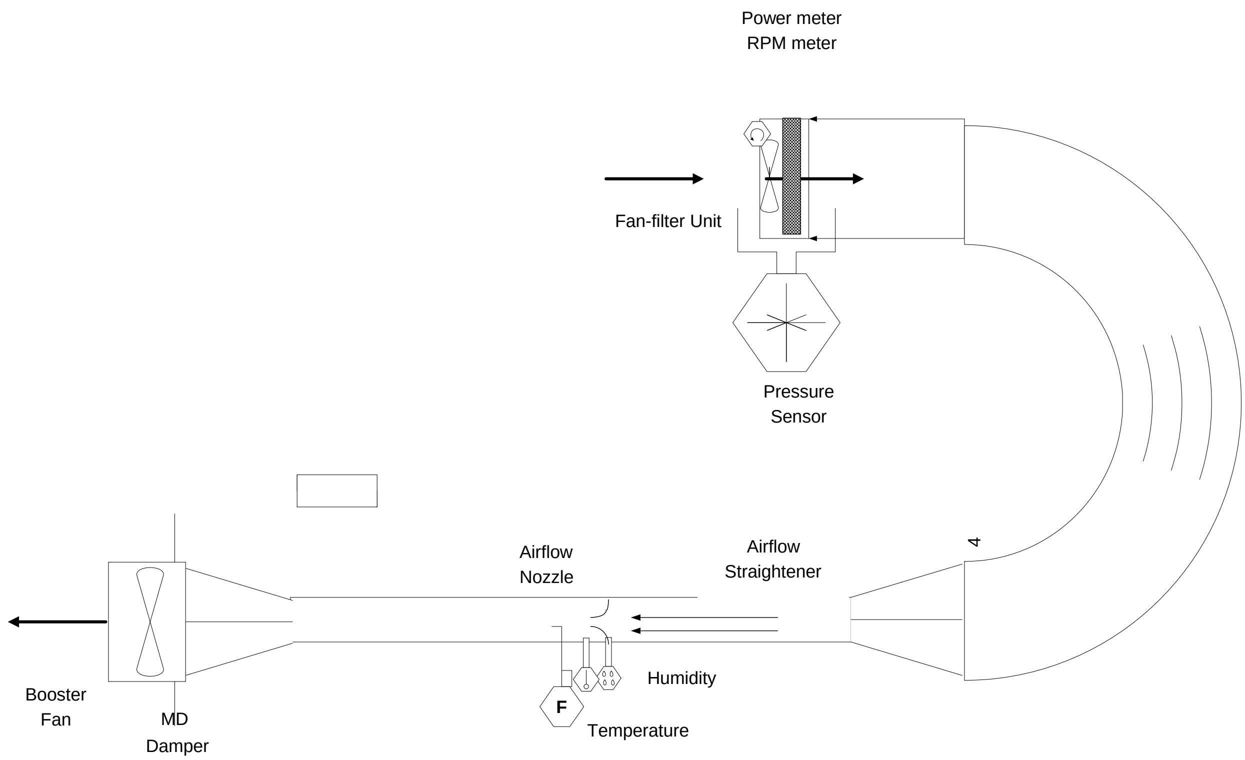


Figure 13 Test rig with a shortened duct length

The findings and evaluations are significant in that 1) the size of test rig can be practically reduced significant, requiring minimal laboratory space to set up the test rig while saving costs (material, labor, space), and 2) having the minimal duct length requirement would allow and emulate FFU application in a cleanroom where the space/duct leading to the FFU is normally minimal.

9.5 FFU Characterization Reports

For each of the FFU tested in LBNL, we generate individual reports on the characterization for each FFUS studied in this project. As a benefit for participants in this research project, each report was submitted to its respective supplier in confidence. This appendix includes the results from laboratory and modeling characterization, and contains no specific information on FFU models or manufacturer names. Each report was numbered or dated randomly, i.e., LBID 2588-1 through 17, without any indication about the order in FFU receipt or testing dates whatsoever.

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-1

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

July 25, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-1

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

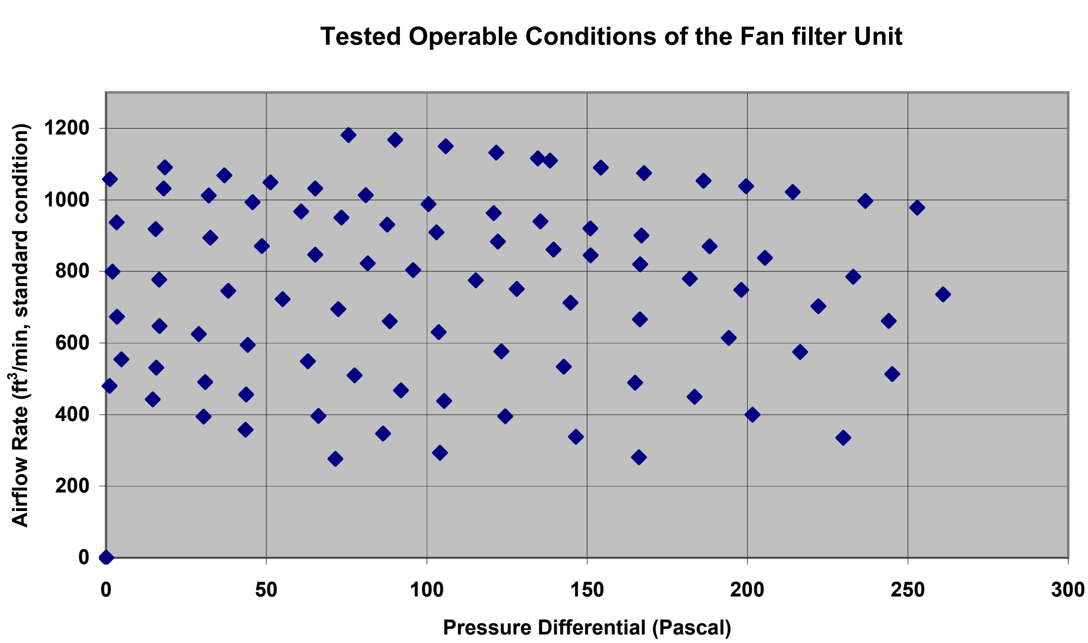
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboaratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

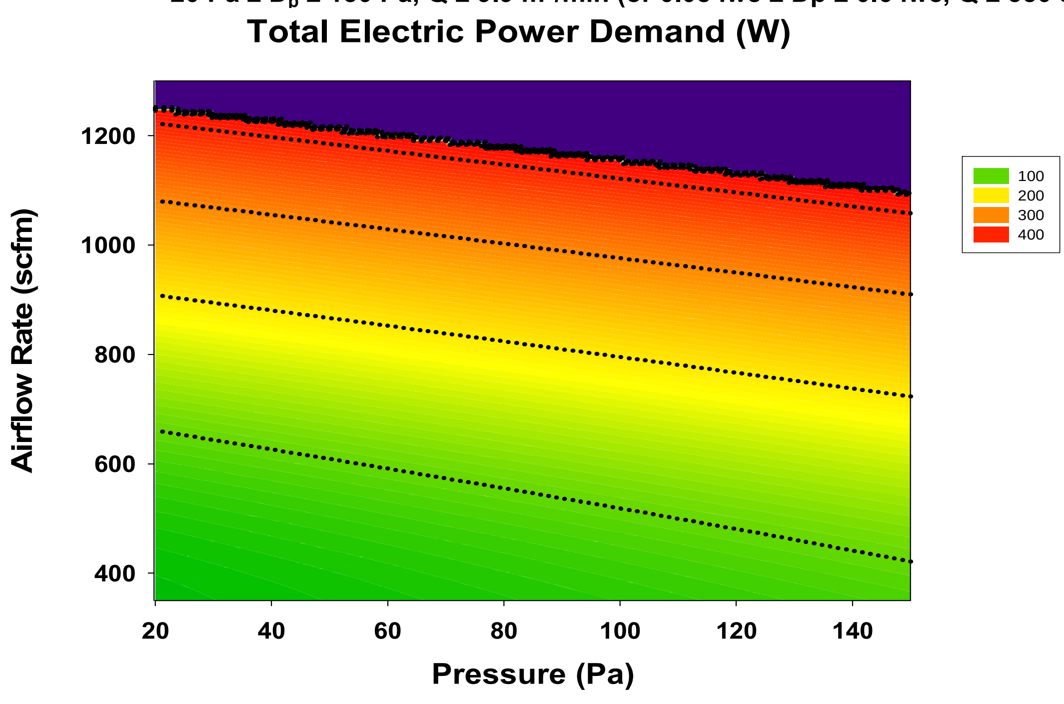
R^2 = **0.999**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	8.45E+01
C_1 =	-4.21E-02
C_2 =	-2.67E-01
C_{11} =	3.99E-04
C_{12} =	8.12E-04
C_{22} =	4.16E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



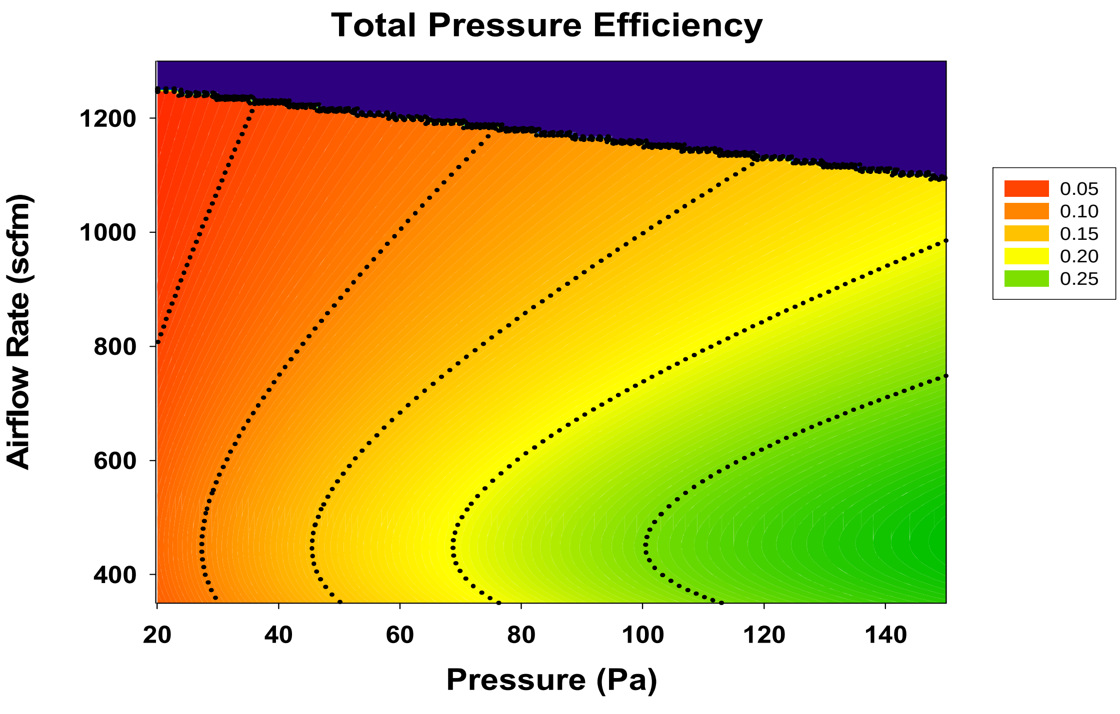
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion: 1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-2

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 8, 2006

Disclaimer

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The project is funded by the California Energy Commission’s Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-2

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

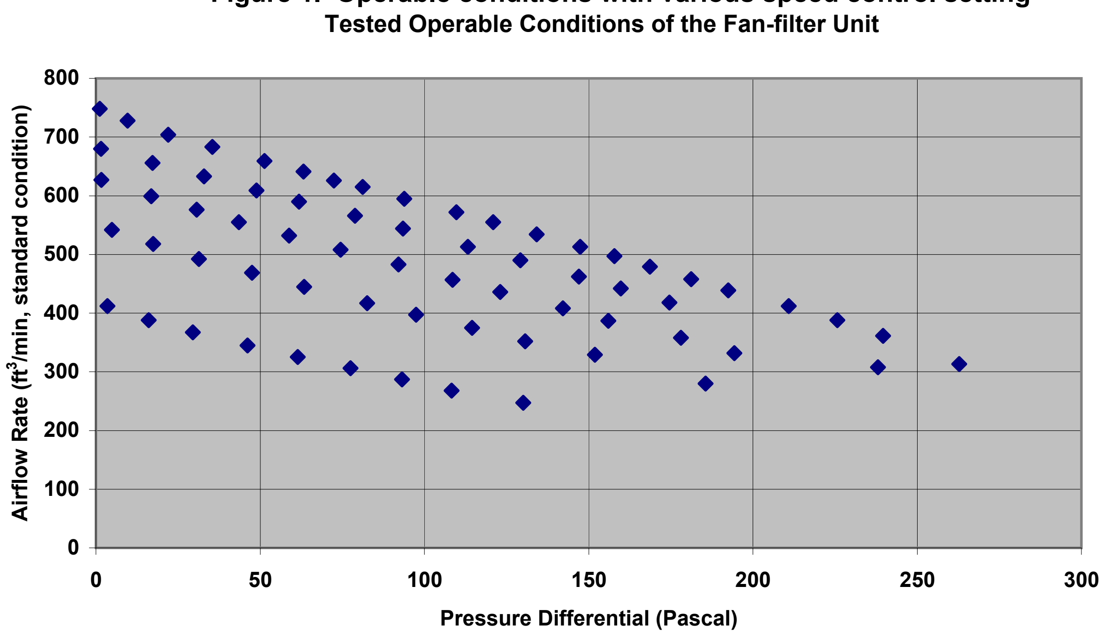
LBNL Tracking

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboaratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

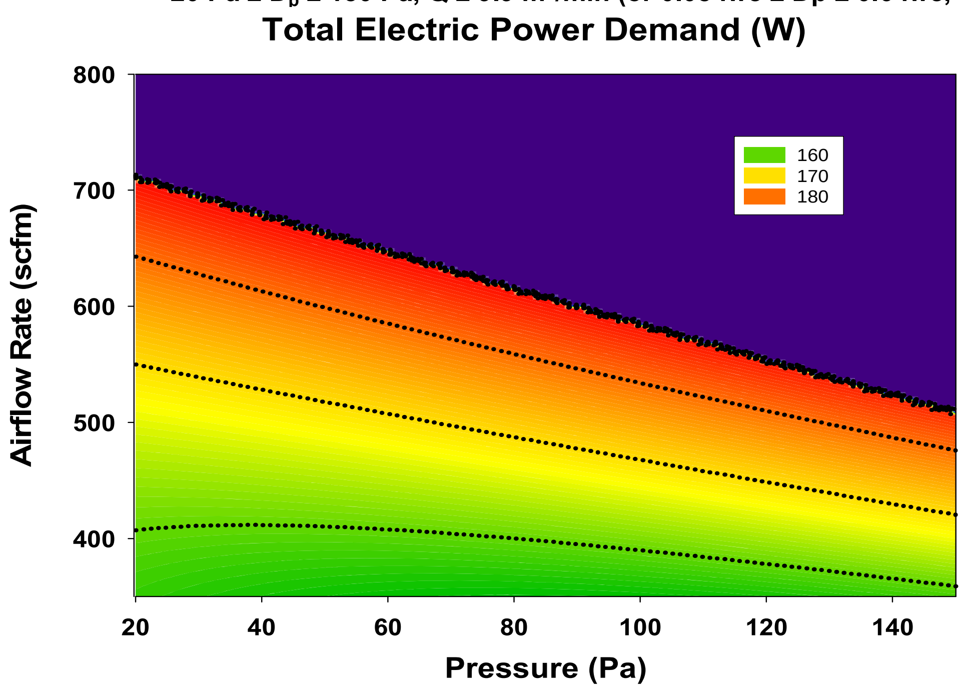
Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

R^2 = 0.995

where	D_p	is the pressure differential across the fan filter unit, in Pascal
	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	C_0 =	1.75E+02
	C_1 =	-4.33E-01
	C_2 =	-1.00E-01
	C_{11} =	6.78E-04
	C_{12} =	9.26E-04
	C_{22} =	1.58E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



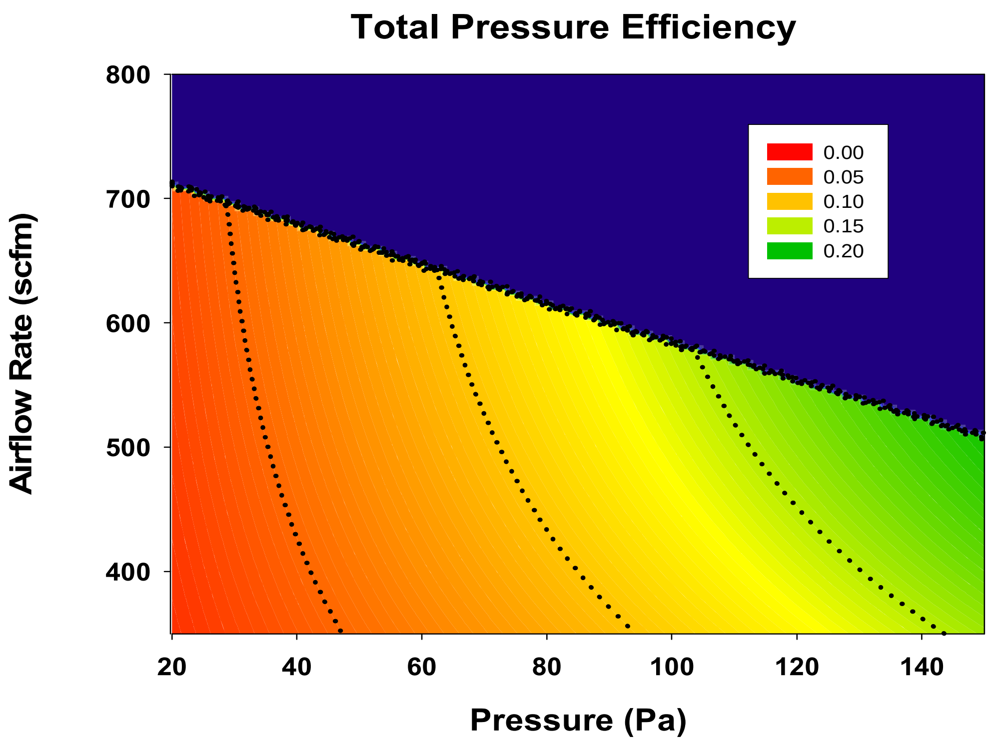
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:

1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-3

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 8, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-3

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

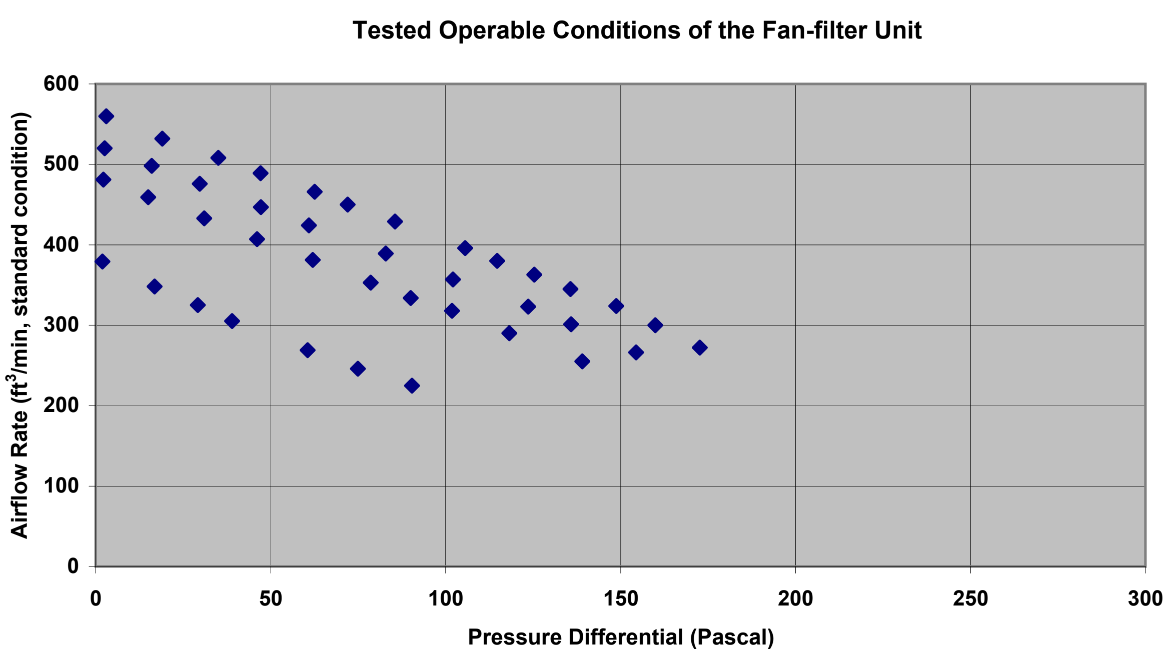
LBNL Tracking

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboaratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using the following equation.

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Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

$R^2 =$ **1.000**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

$C_0 =$ 1.45E+02

$C_1 =$ -7.18E-01

$C_2 =$ -4.38E-01

$C_{11} =$ 1.78E-03

$C_{12} =$ 2.40E-03

$C_{22} =$ 7.23E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)

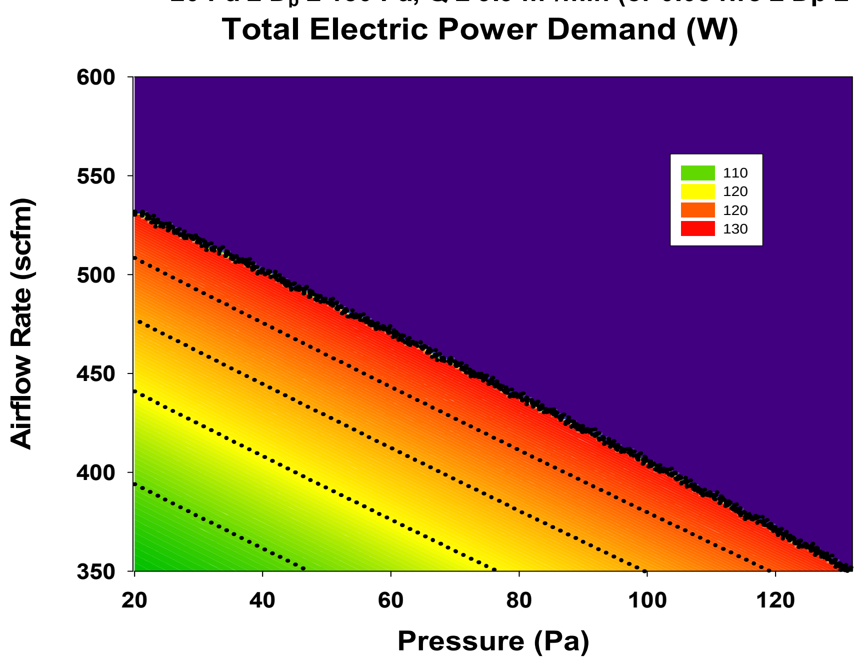

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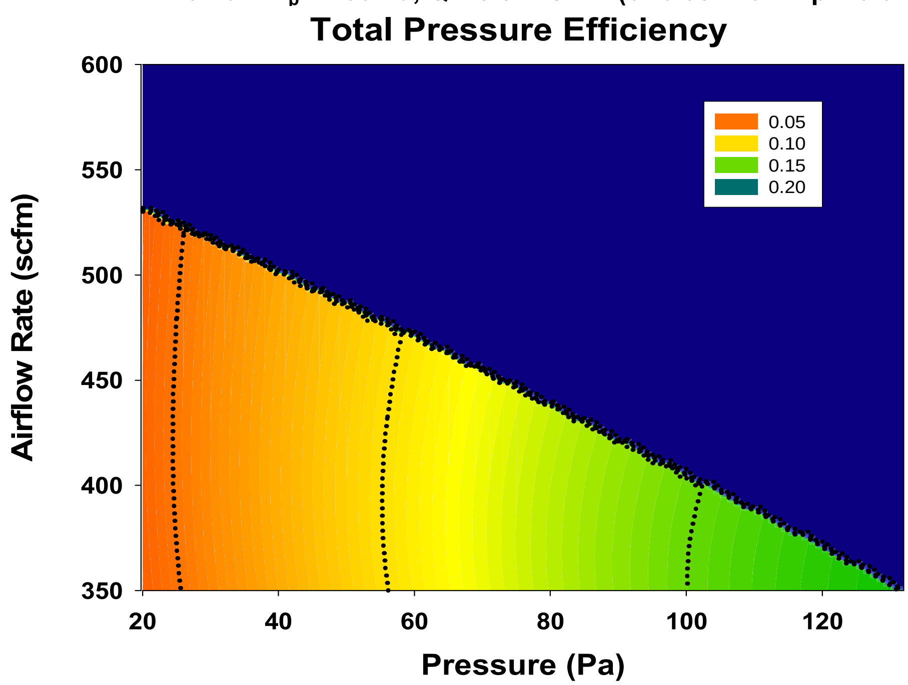
Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:

1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-4

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 10, 2006

Disclaimer

Acknowledgements

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Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-4

Reporting Characteristics of the Unit Based on Manufacturer's Shipment
Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

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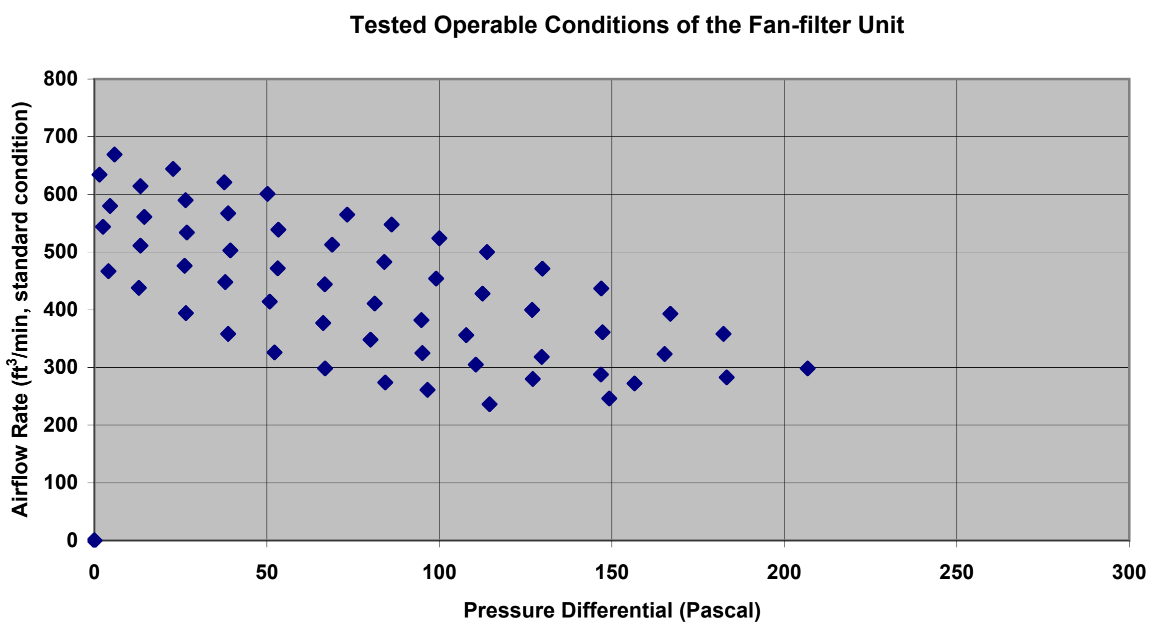
Figure 1. Operable conditions with various speed control setting



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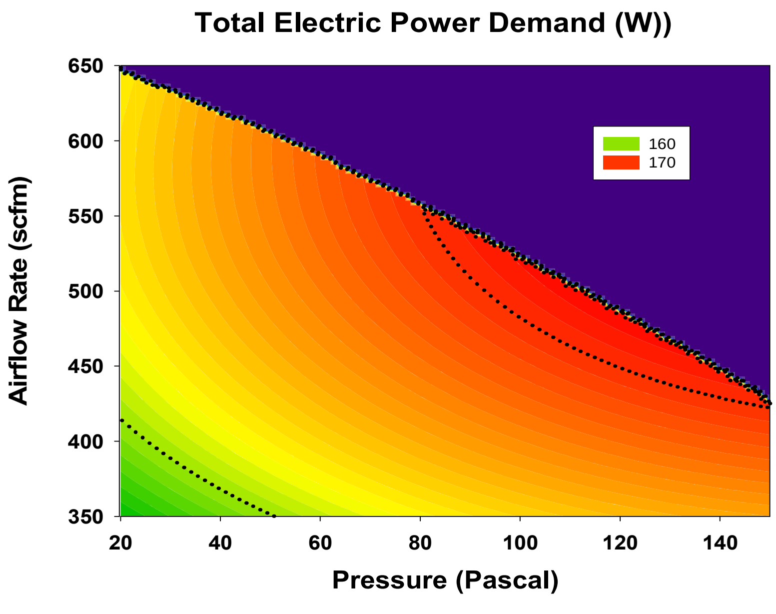
R^2 = **1.000**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	1.22E+02
C_1 =	7.67E-02
C_2 =	1.37E-01
C_{11} =	-3.32E-04
C_{12} =	1.29E-04
C_{22} =	-1.22E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



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where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
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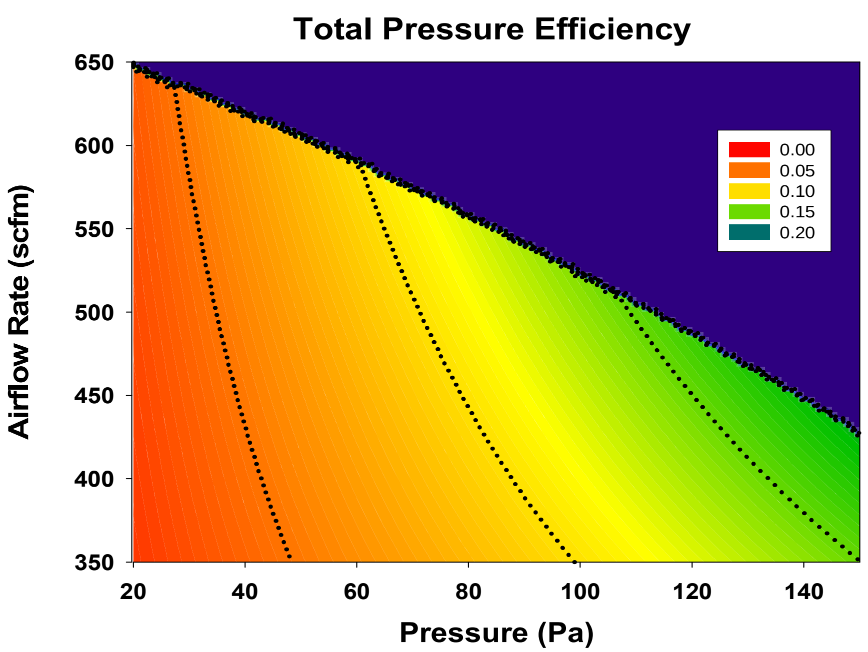

Note of unit conversion:

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1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-5

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 11, 2006

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Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-5

Reporting Characteristics of the Unit Based on Manufacturer's Shipment
Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

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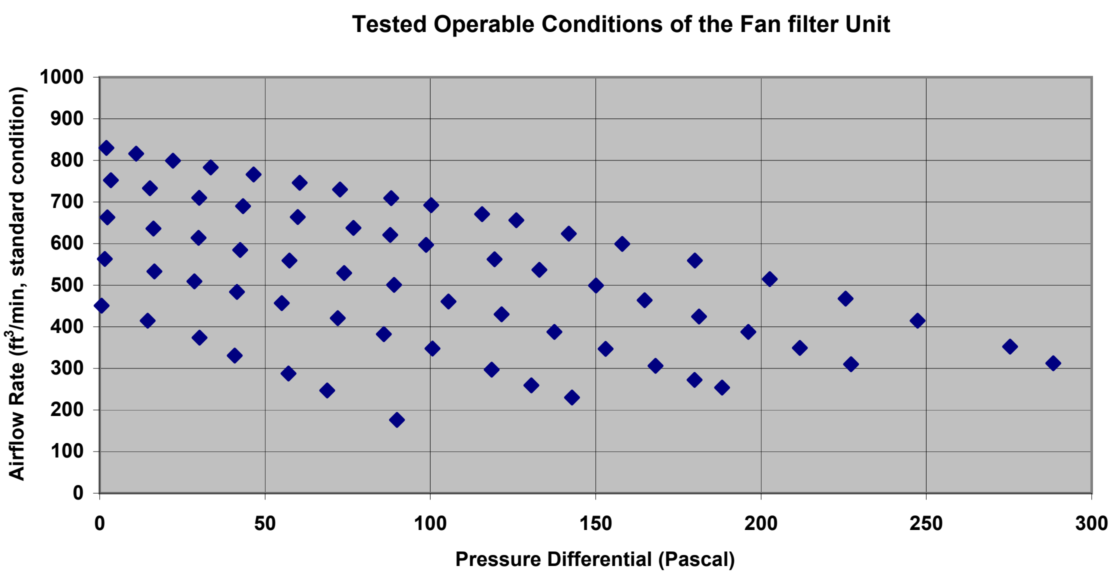
Figure 1. Operable conditions with various speed control setting



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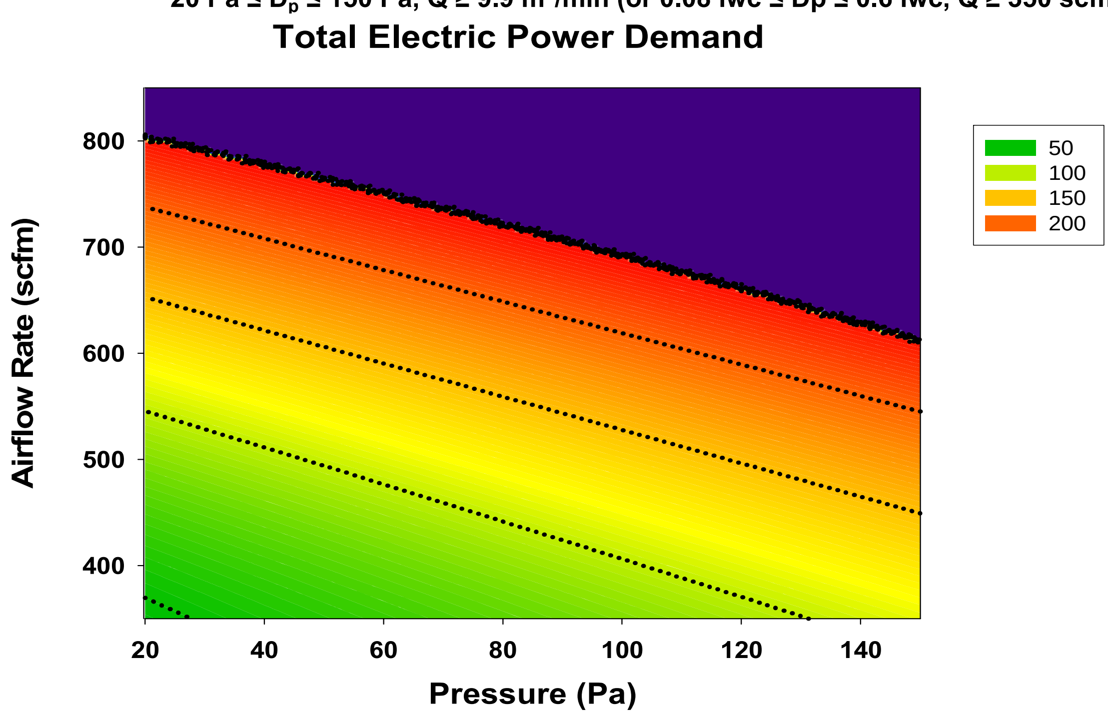
R^2 = 0.999

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	7.68E+01
C_1 =	-1.34E-01
C_2 =	-3.32E-01
C_{11} =	7.09E-04
C_{12} =	1.44E-03
C_{22} =	6.42E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



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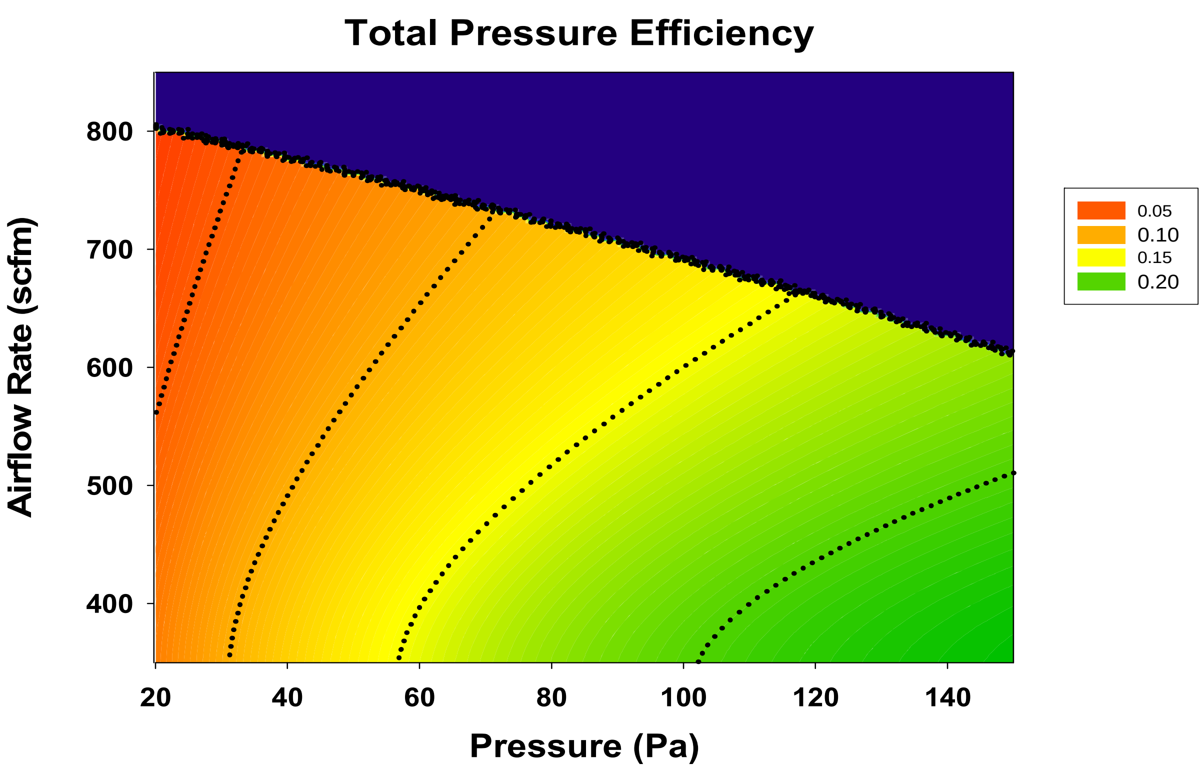

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Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-6

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 11, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-6

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

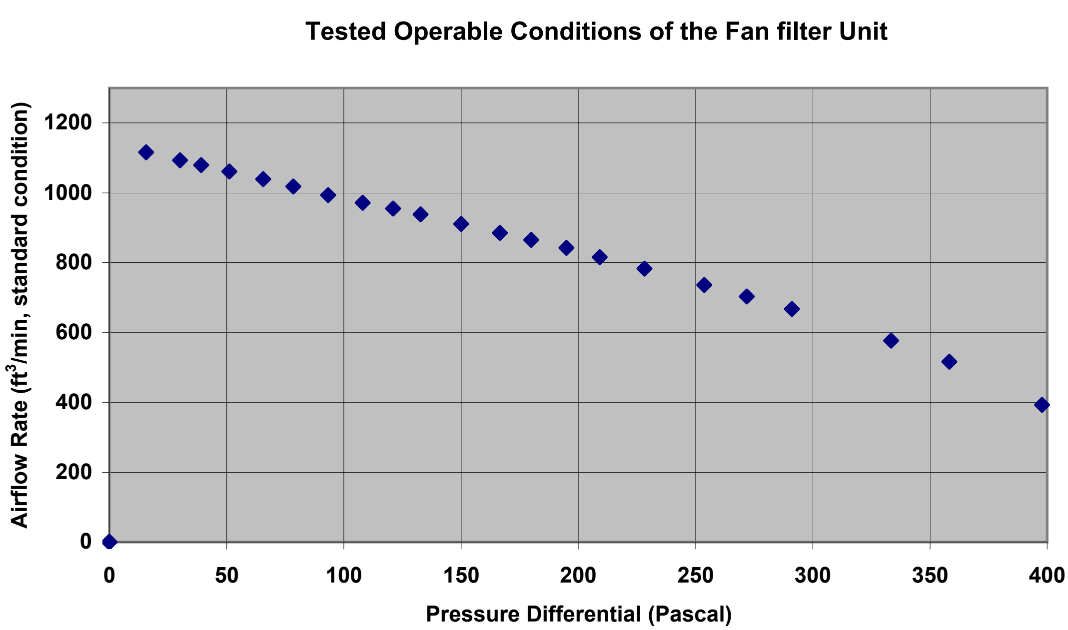
LBNL Tracking

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboaratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using either of the following equations.

Each of the equations is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-squares of the regression are included, which explain the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_{01} + C_1 \times D_p + C_{11} \times D_p^2$

$R_1^2 =$ **0.983**

Electric Power Demand (Watt) = $C_{02} + C_2 \times Q + C_{22} \times Q^2$

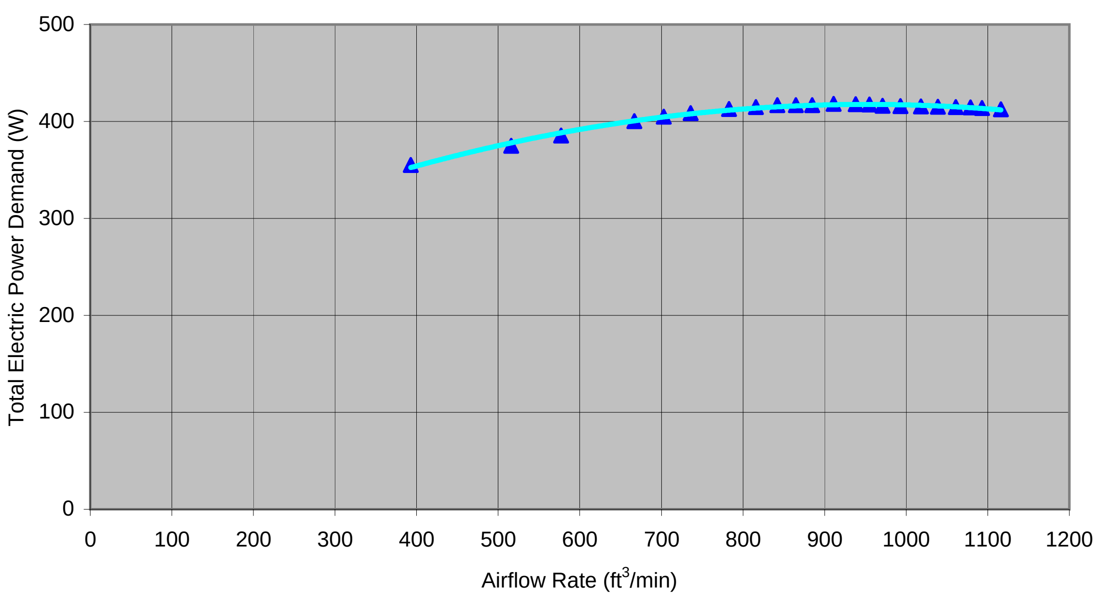
$R_2^2 =$ **0.993**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_{01} =	405.94	C_{02} =	228.58
C_1 =	2.13E-01	C_2 =	0.3972
C_{11} =	-8.00E-04	C_{22} =	-0.0002

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Airflow Rate (ft^3/min)

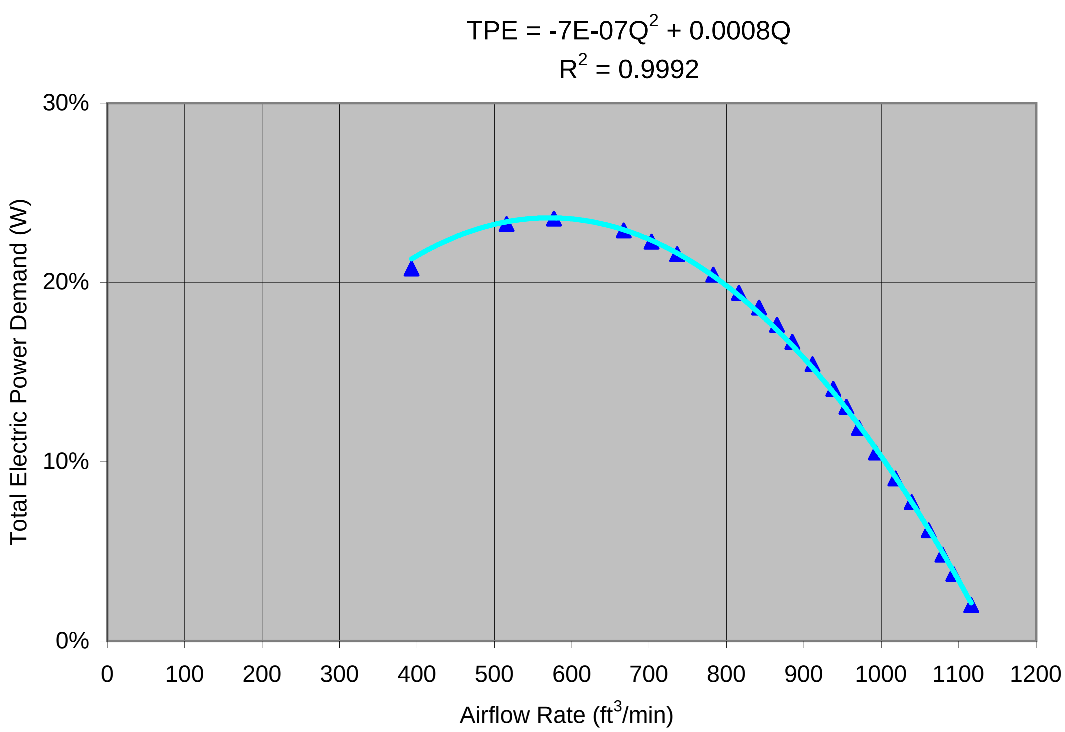
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:	1 kPa = 4.015 inch water column
	1 m/s = 196.9 feet per minute (fpm)
	1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-7

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 17, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-7

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

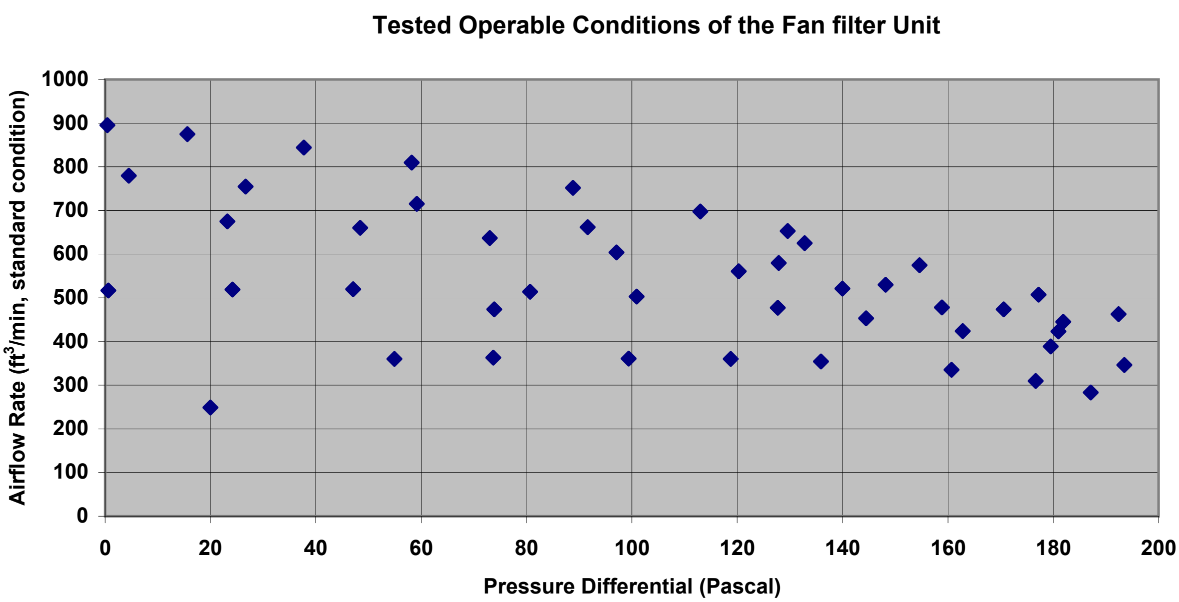
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboaratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

$R^2 =$ **0.994**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

$C_0 =$ 3.22E+01

$C_1 =$ -1.01E-01

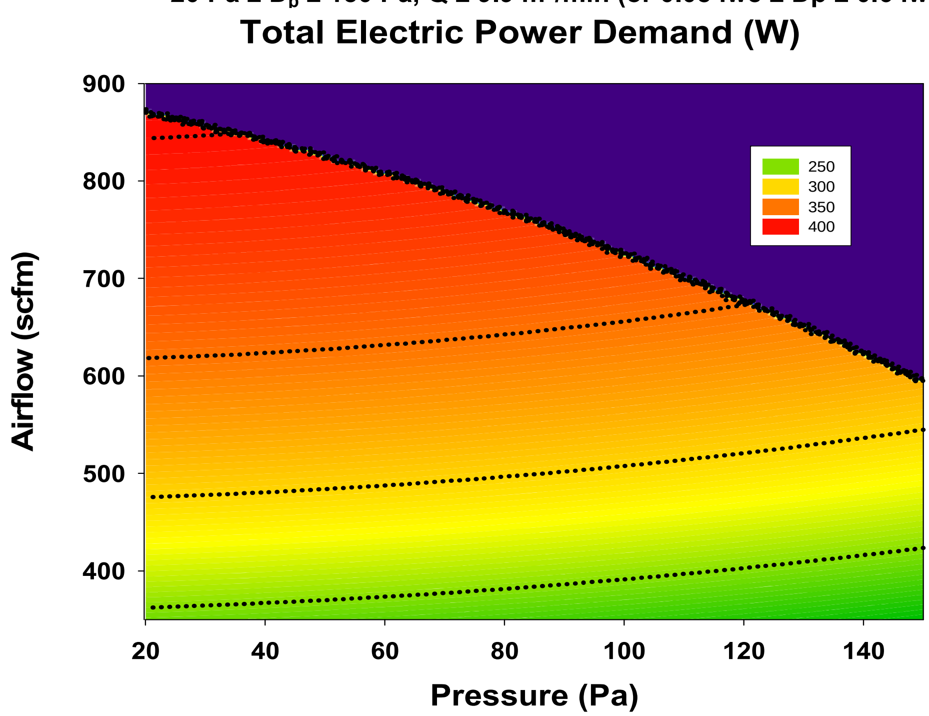
$C_2 =$ 7.33E-01

$C_{11} =$ -9.96E-04

$C_{12} =$ 1.28E-04

$C_{22} =$ -3.51E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



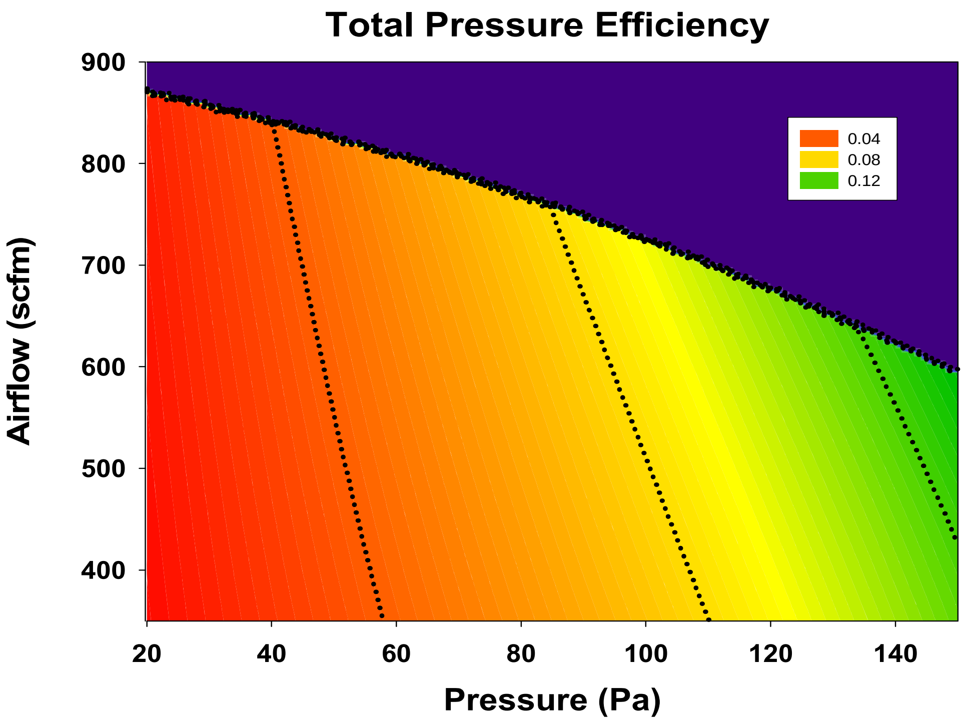
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:	1 kPa = 4.015 inch water column
	1 m/s = 196.9 feet per minute (fpm)
	1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-8

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 17, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-8

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

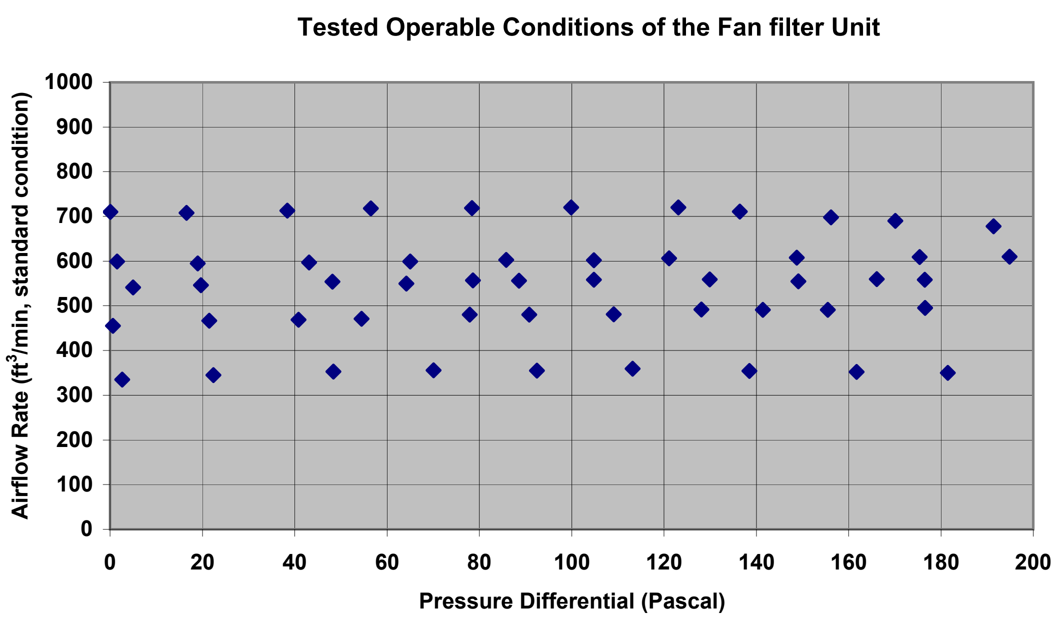
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboaratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

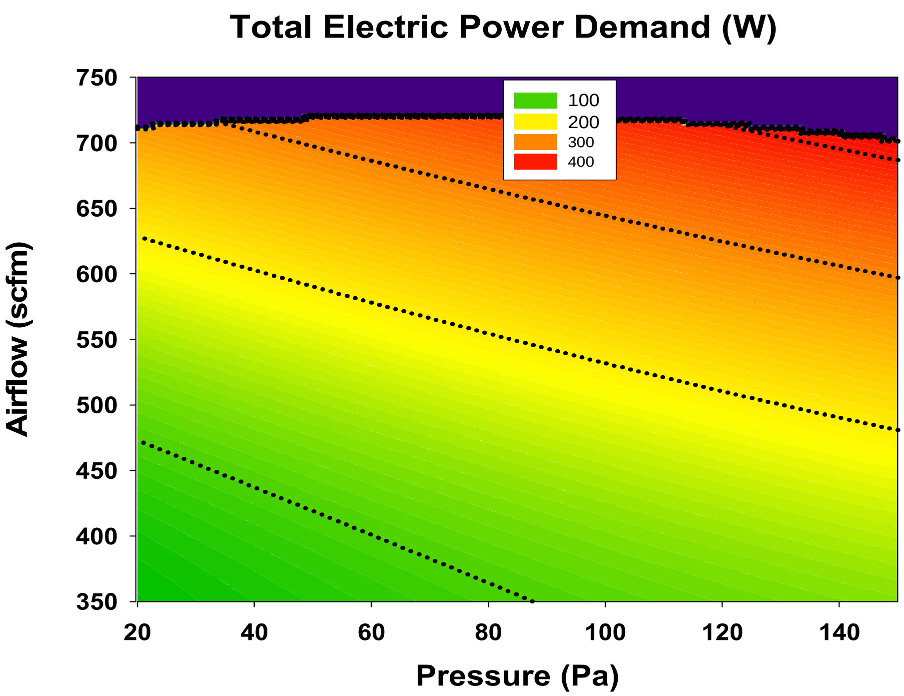
R^2 = **0.999**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	1.72E+02
C_1 =	-6.45E-02
C_2 =	-7.81E-01
C_{11} =	-5.77E-04
C_{12} =	1.88E-03
C_{22} =	1.26E-03

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



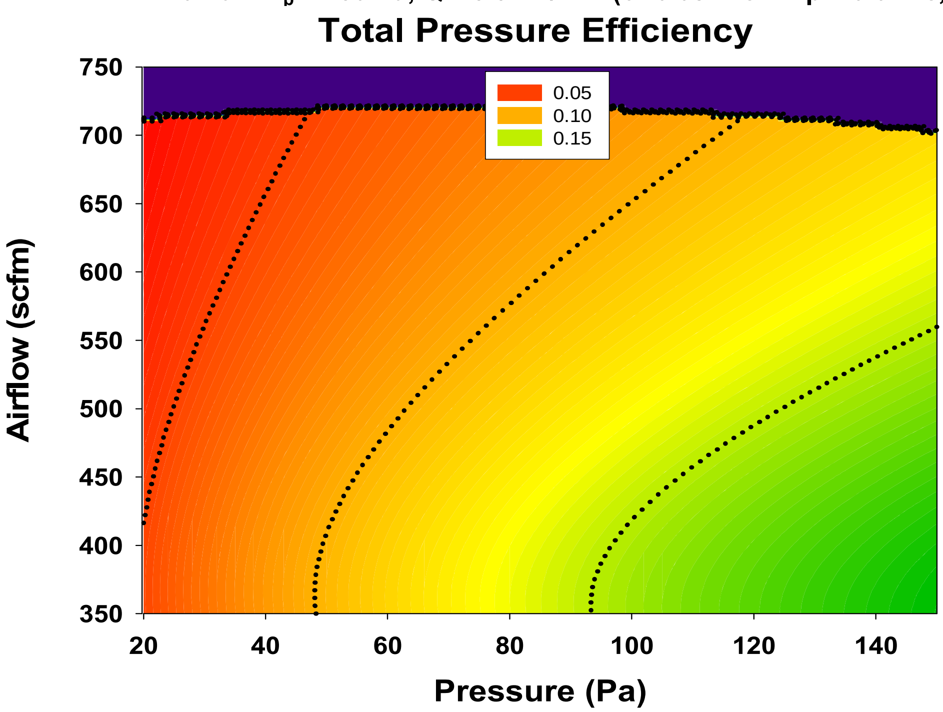
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion: 1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-9

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 18, 2006

Disclaimer

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Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-9

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

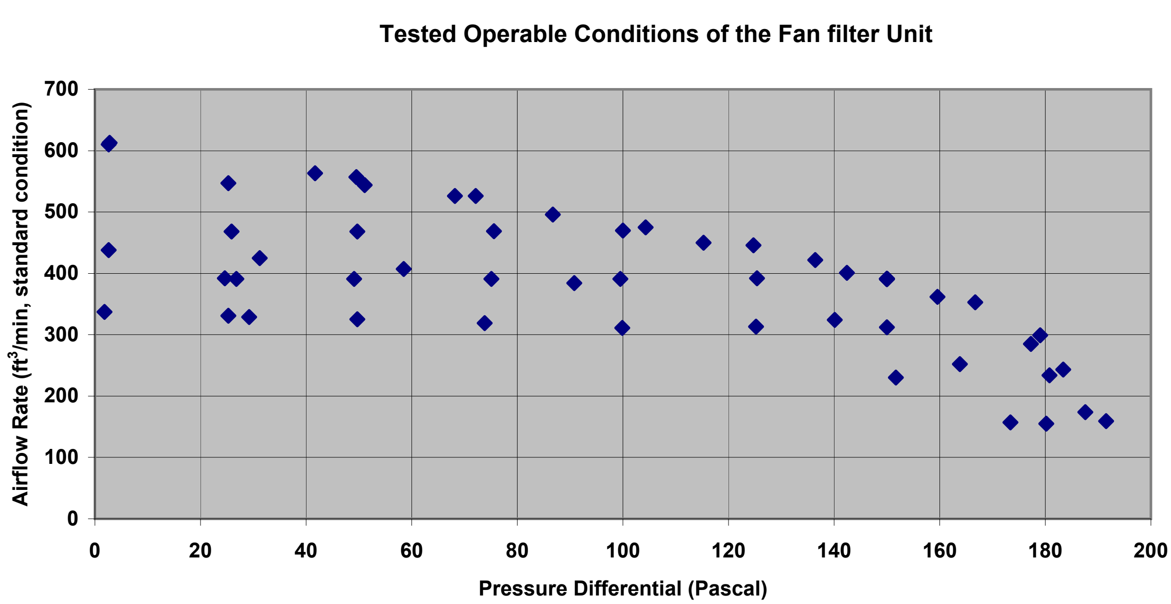
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboaratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

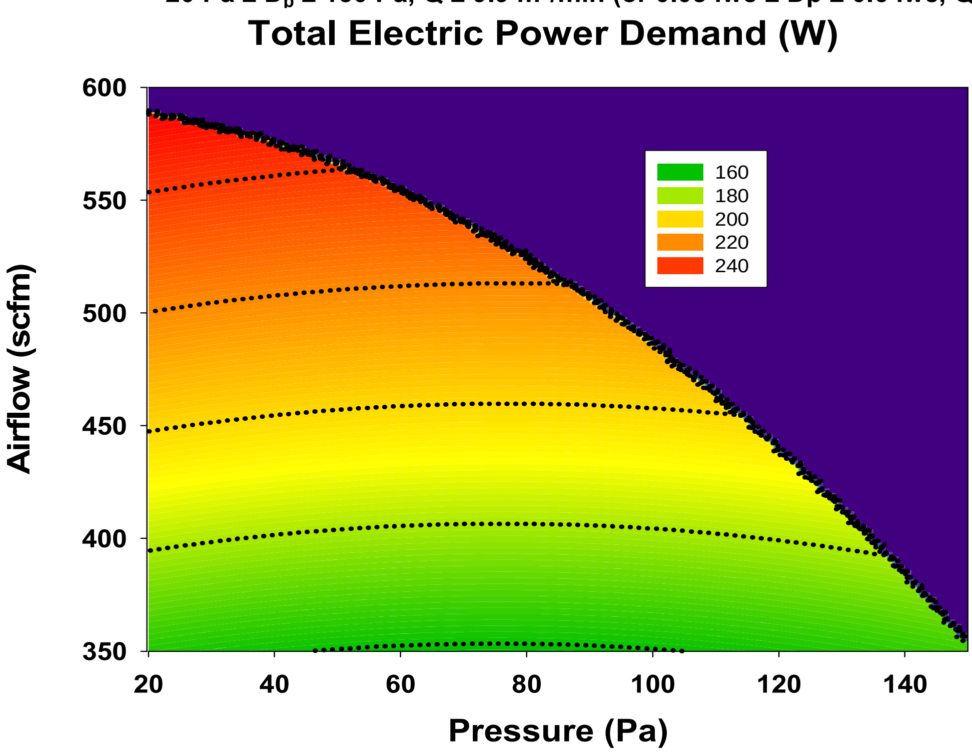
$R^2 =$ **0.997**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

$C_0 =$	3.32E+01
$C_1 =$	-2.01E-01
$C_2 =$	3.84E-01
$C_{11} =$	1.43E-03
$C_{12} =$	-4.37E-05
$C_{22} =$	-6.15E-06

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Pressure (Pa)

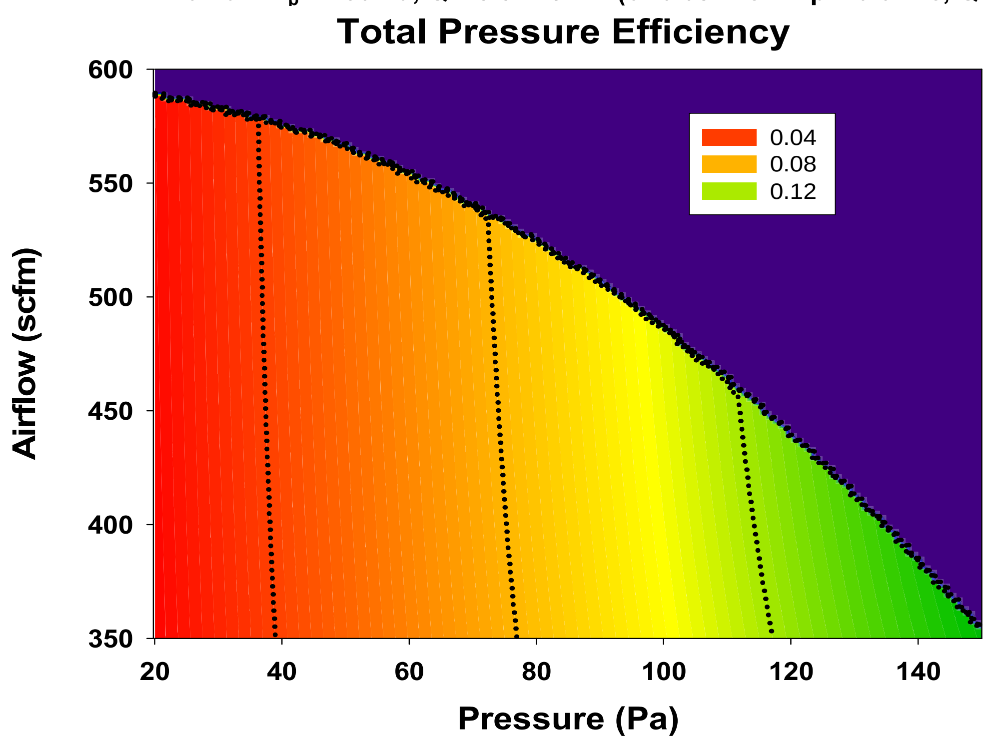
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:

1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-10

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

August 18, 2006

Disclaimer

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Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-10

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

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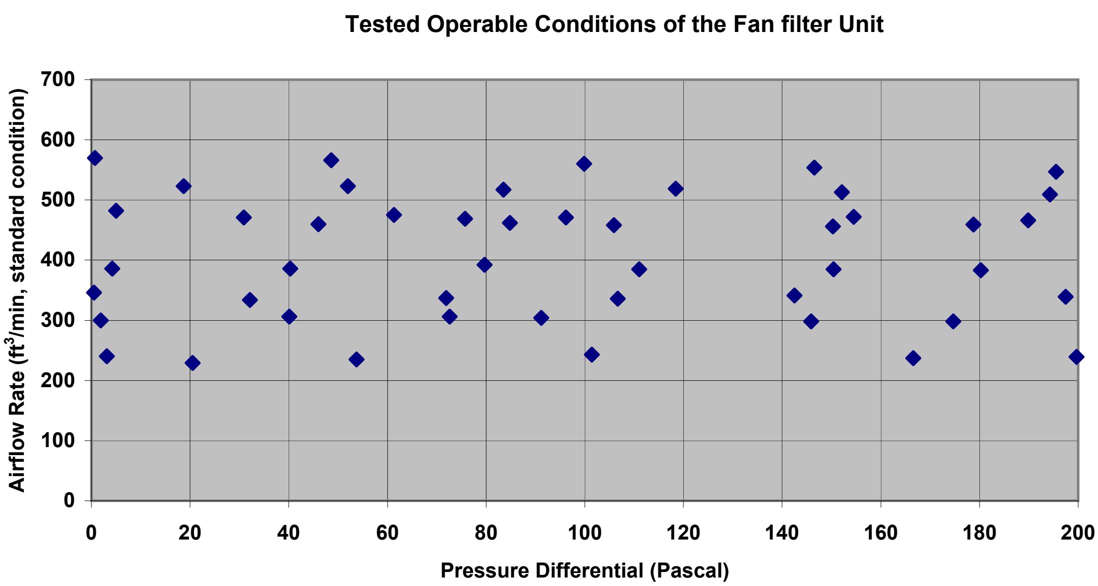
Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electirc power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electirc power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

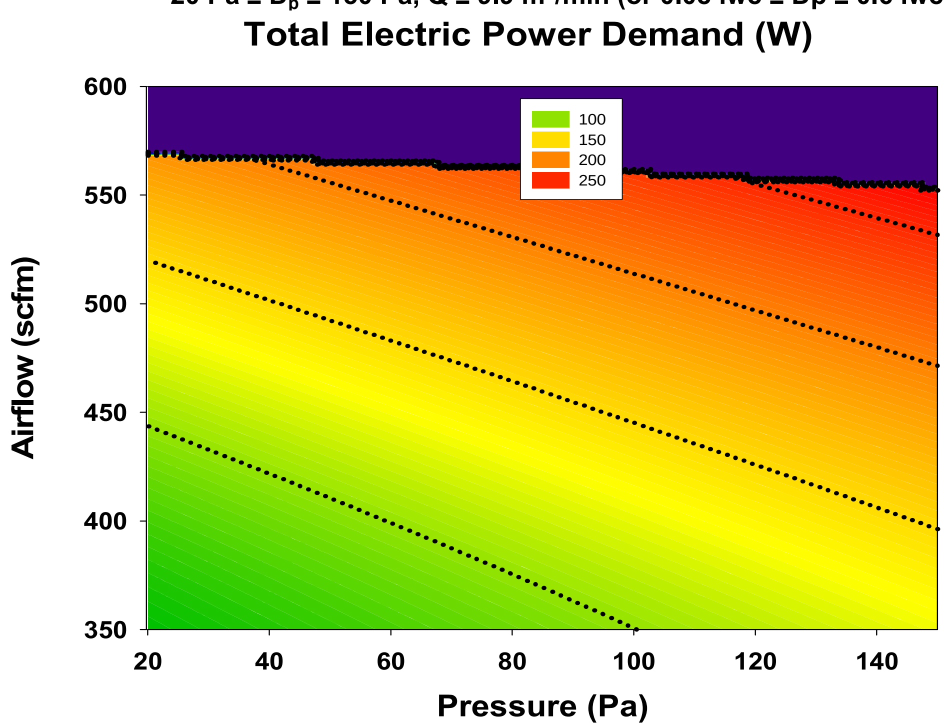
$R^2 =$ **0.999**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

$C_0 =$	8.59E+01
$C_1 =$	1.78E-01
$C_2 =$	-5.35E-01
$C_{11} =$	4.97E-05
$C_{12} =$	9.66E-04
$C_{22} =$	1.22E-03

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions:
20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



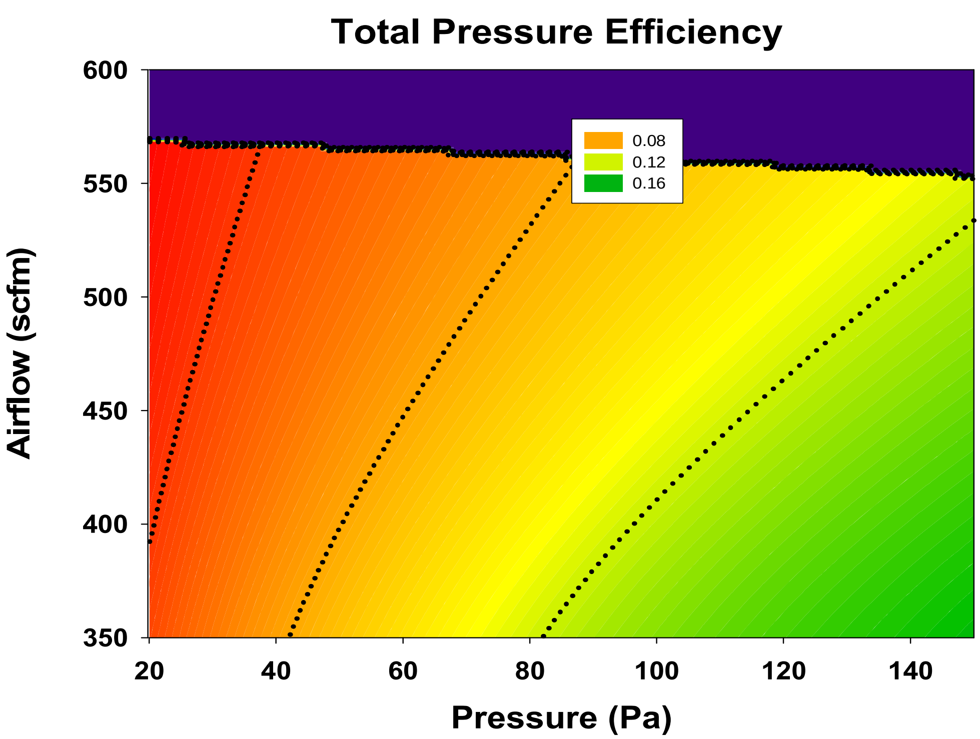
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions:
20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:

1 kPa = 4.015 inch water column
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1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-11

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

September 15, 2006

Disclaimer

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Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-11

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

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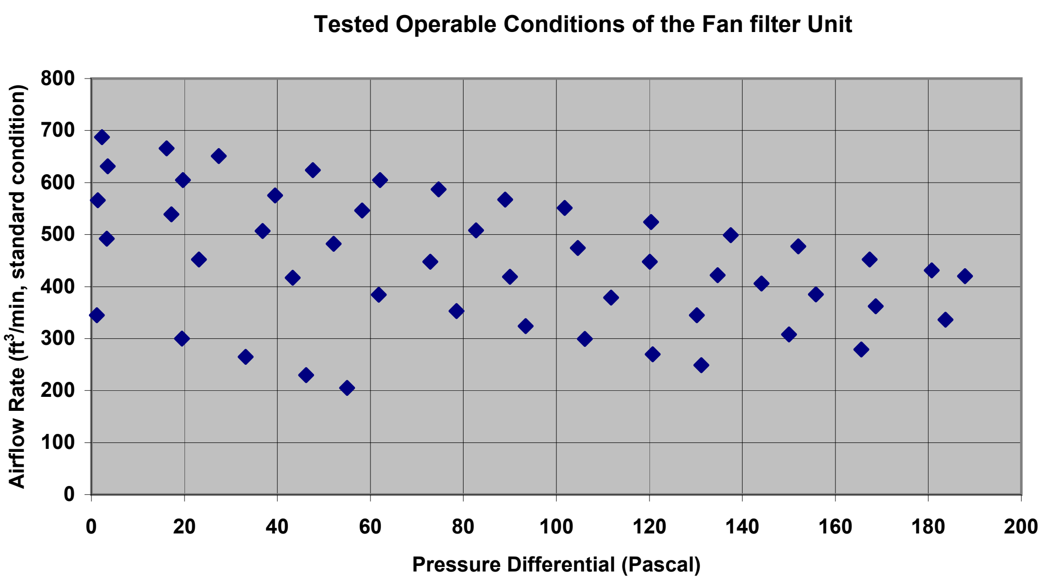
Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

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The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

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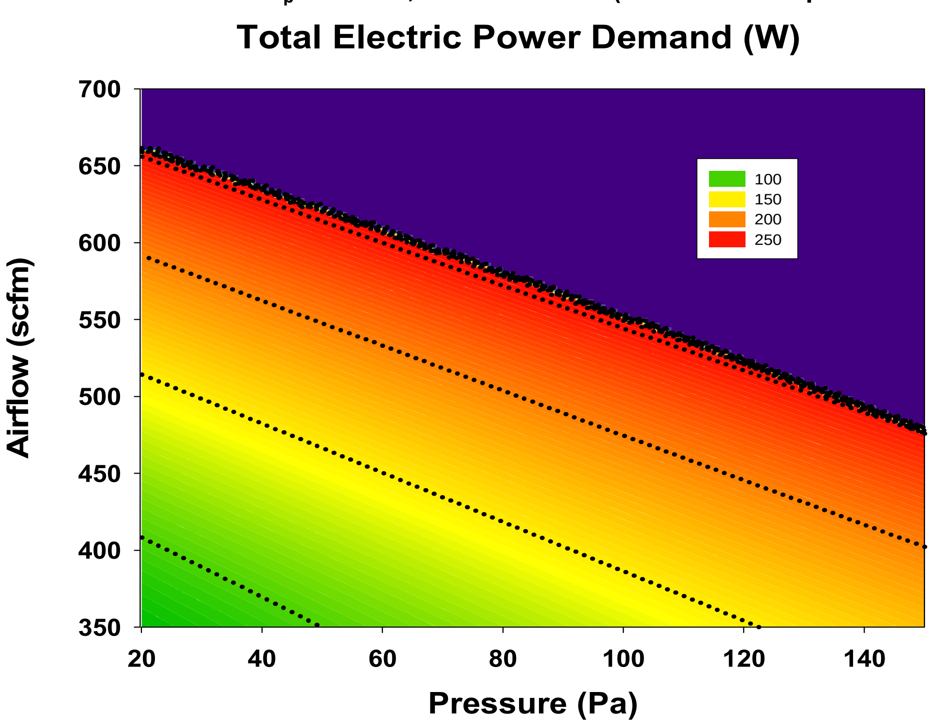
R^2 = 0.999

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	1.08E+02
C_1 =	-1.05E-01
C_2 =	-4.38E-01
C_{11} =	6.95E-04
C_{12} =	1.92E-03
C_{22} =	9.44E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



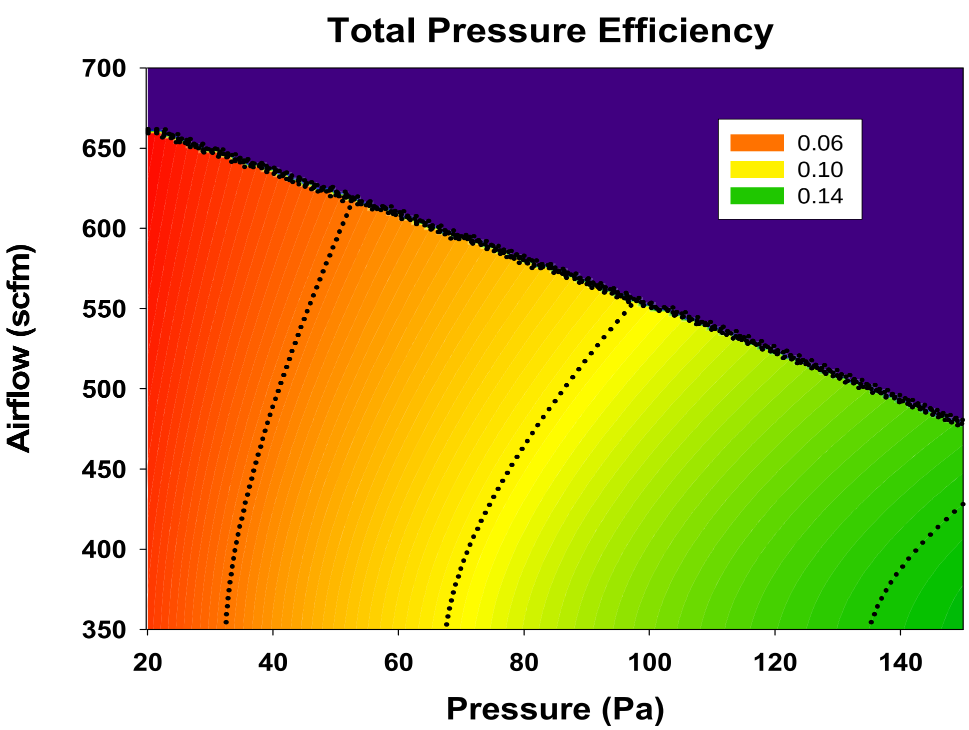
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion: 1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-12

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

September 15, 2006

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Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-12

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

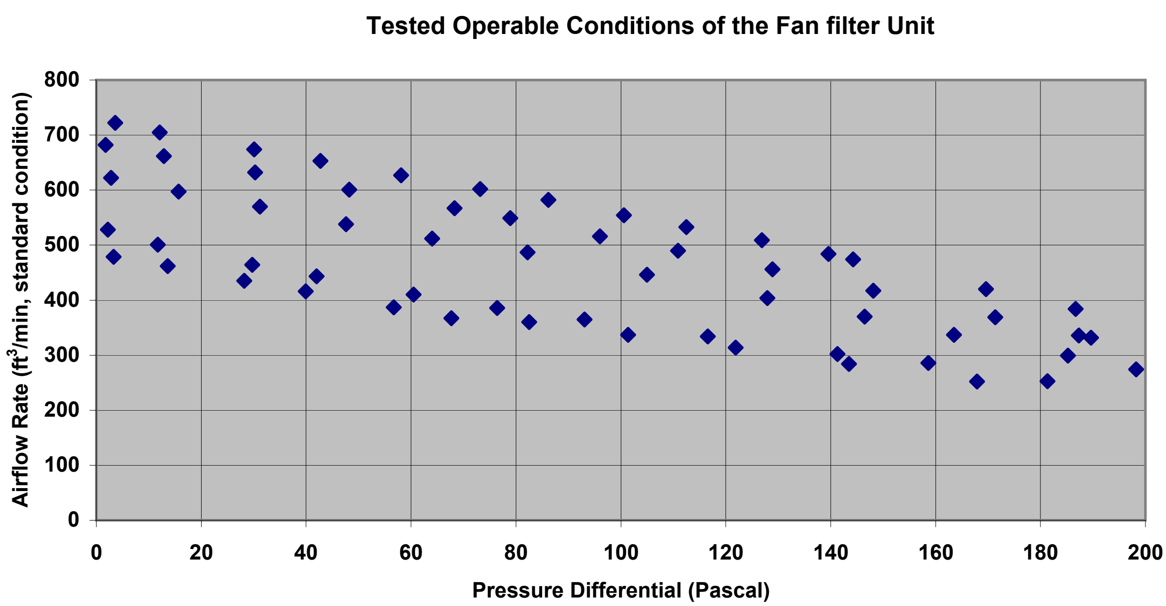
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electric power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electric power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

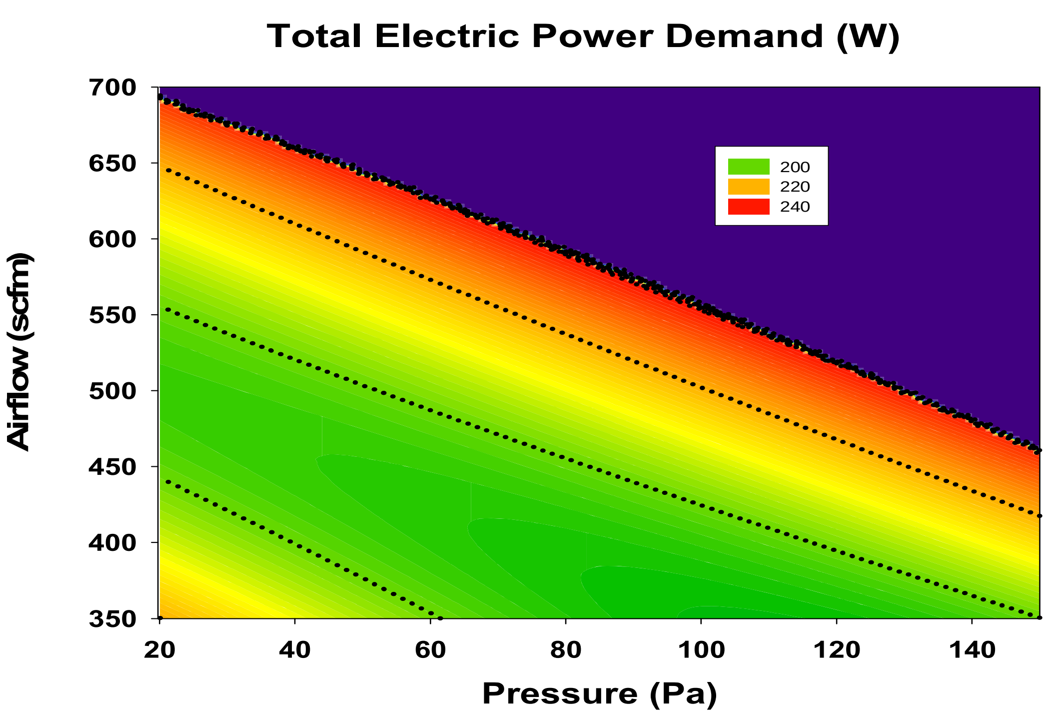
R^2 = 0.999

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	5.04E+02
C_1 =	-2.25E+00
C_2 =	-1.14E+00
C_{11} =	3.72E-03
C_{12} =	4.17E-03
C_{22} =	1.06E-03

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



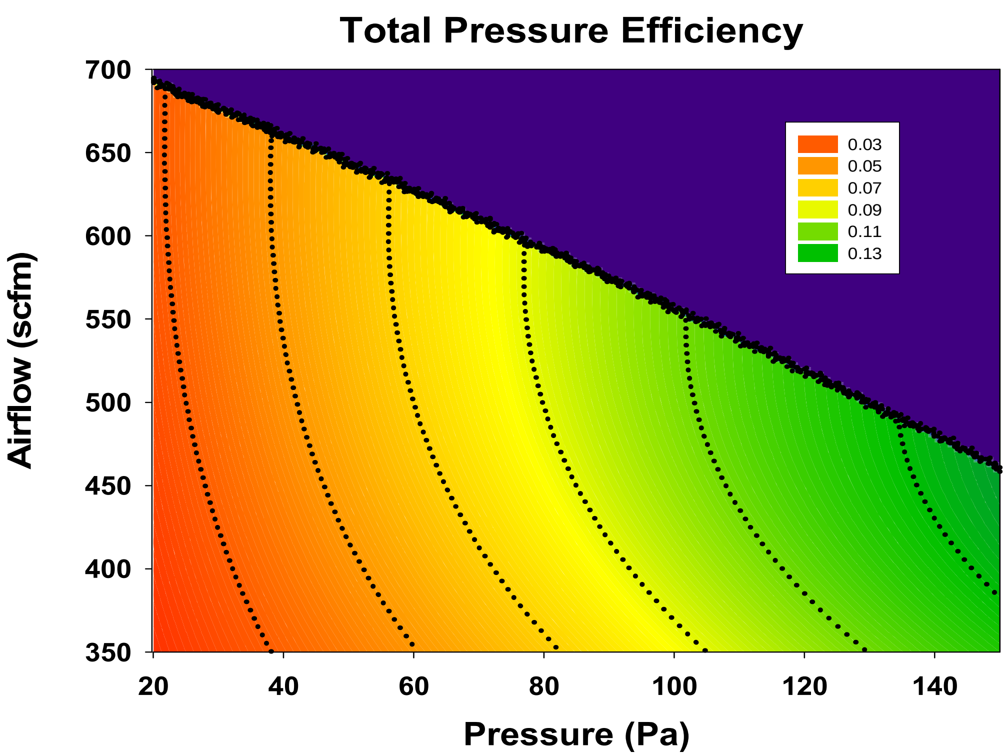
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:

1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-13

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

September 15, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-13

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

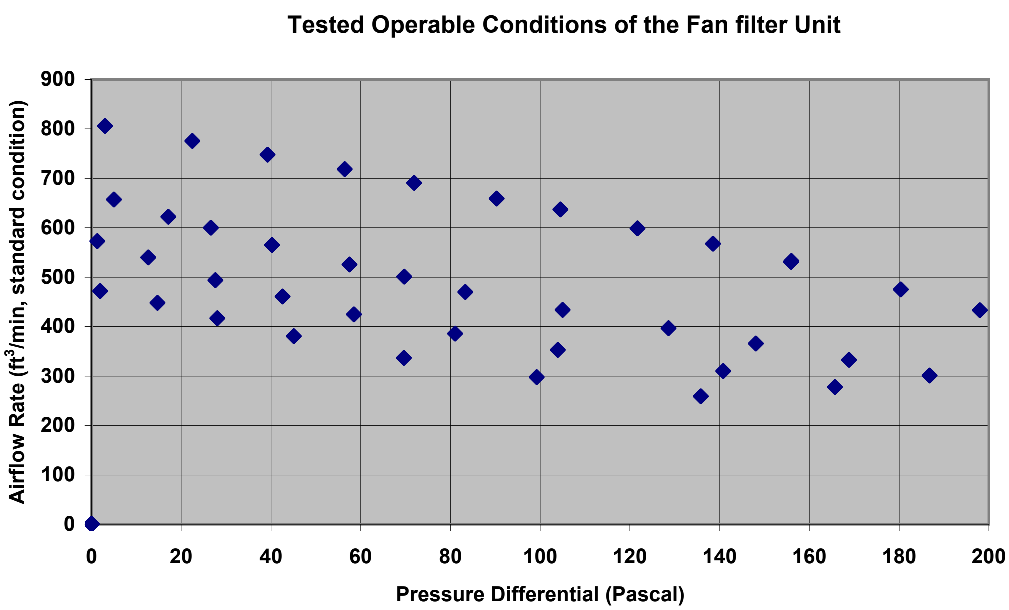
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electric power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electric power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

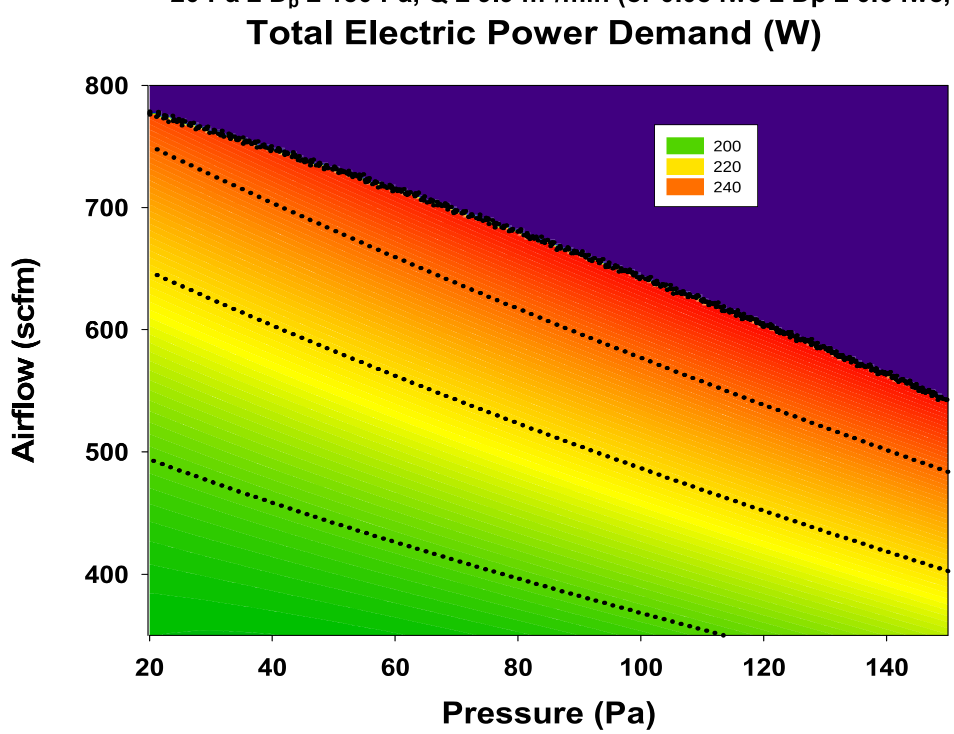
R^2 = 0.999

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	2.27E+02
C_1 =	-5.61E-01
C_2 =	-1.84E-01
C_{11} =	1.21E-03
C_{12} =	1.39E-03
C_{22} =	2.51E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



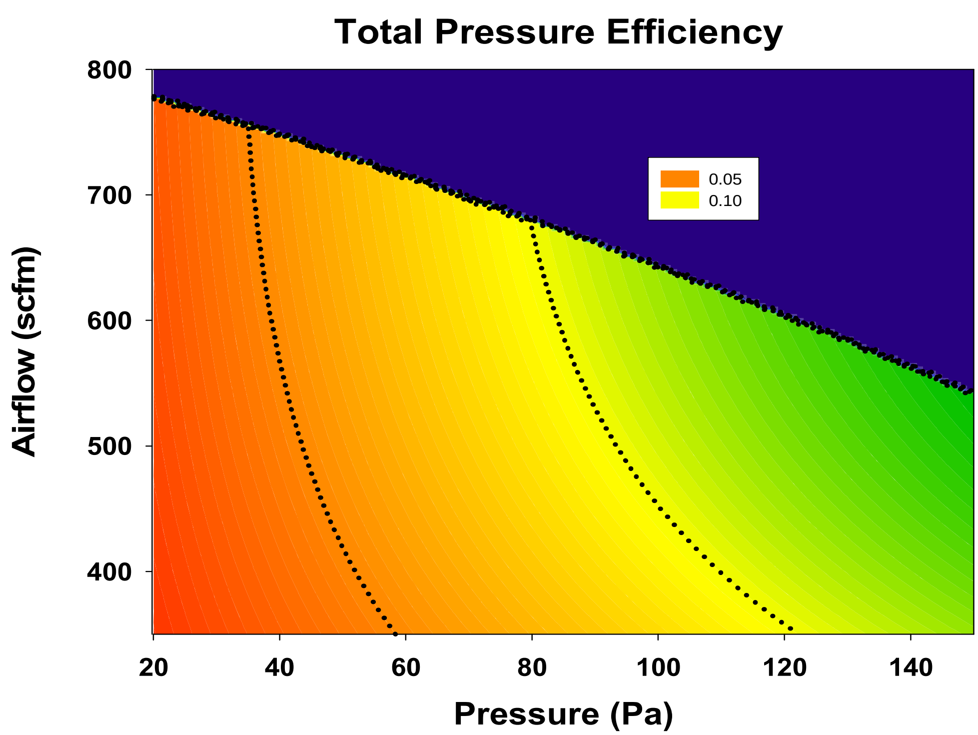
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion: 1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-14

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

September 15, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-14

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

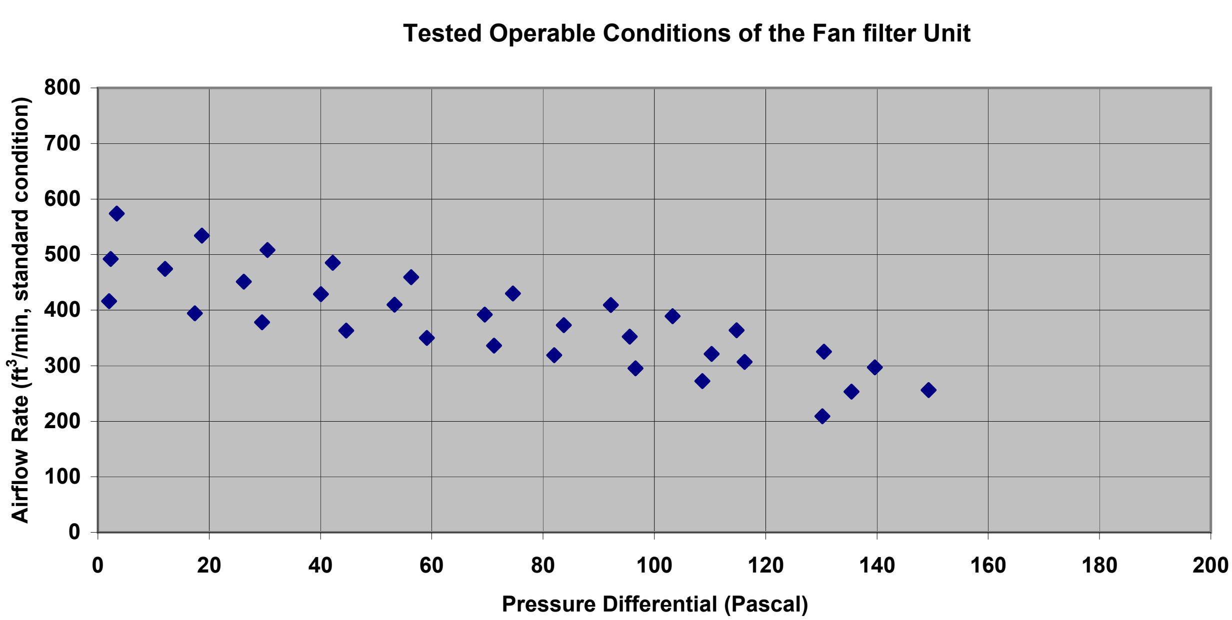
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electric power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electric power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

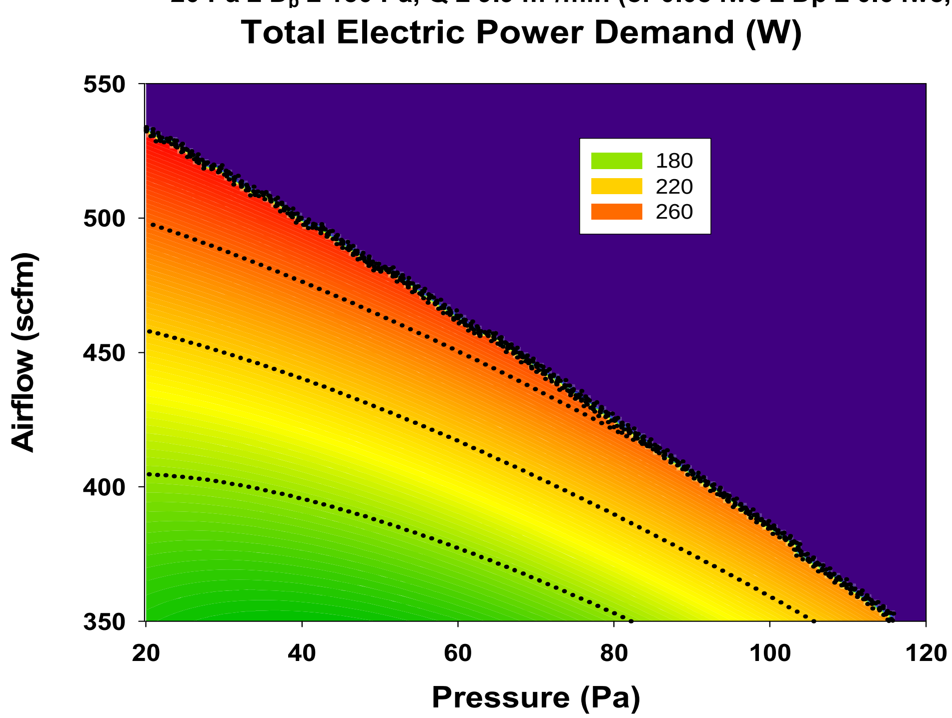
R^2 = 0.996

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	4.58E+02
C_1 =	-4.97E+00
C_2 =	-1.74E+00
C_{11} =	1.52E-02
C_{12} =	1.09E-02
C_{22} =	2.63E-03

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



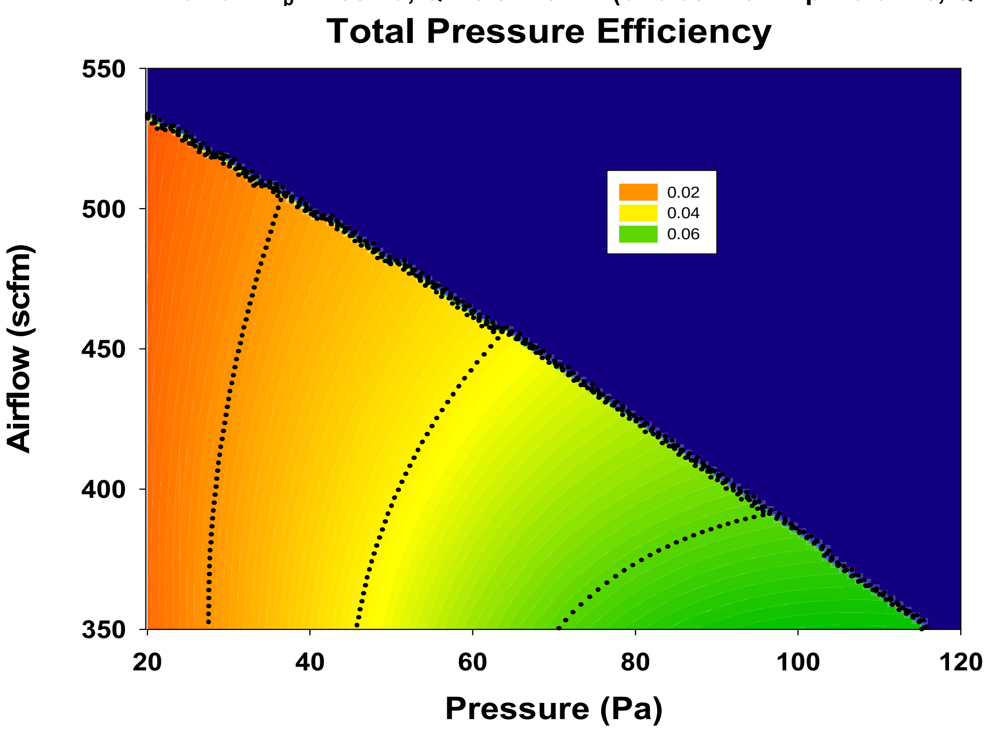
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:	1 kPa = 4.015 inch water column
	1 m/s = 196.9 feet per minute (fpm)
	1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-15

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

September 15, 2006

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Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-15

Reporting Characteristics of the Unit Based on Manufacturer's Shipment
Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

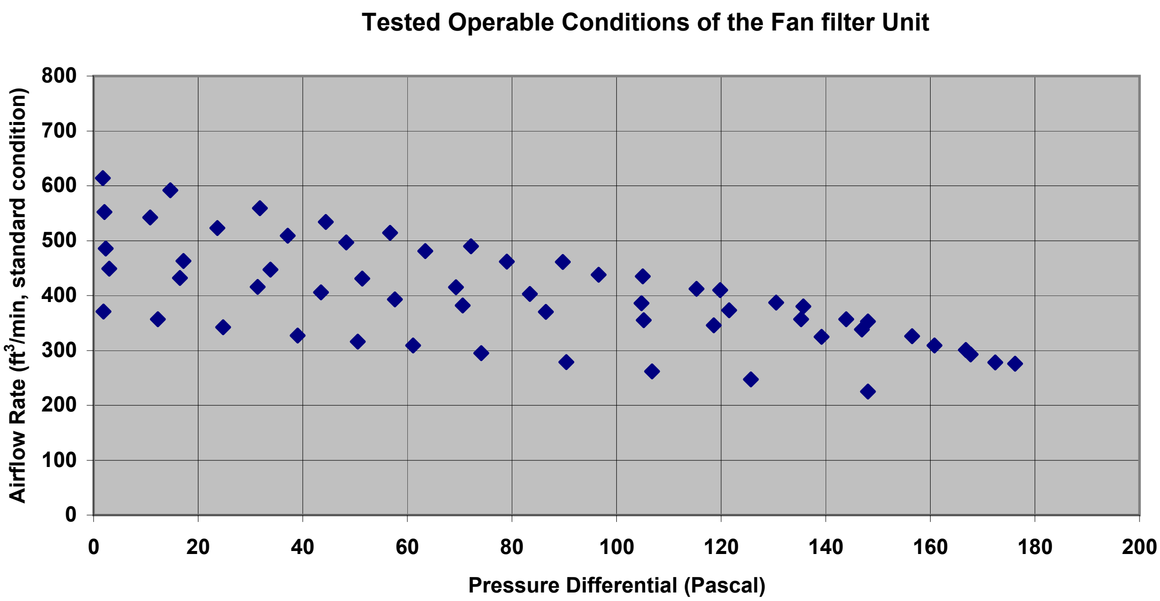
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electric power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electric power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

$R^2 =$ **0.999**

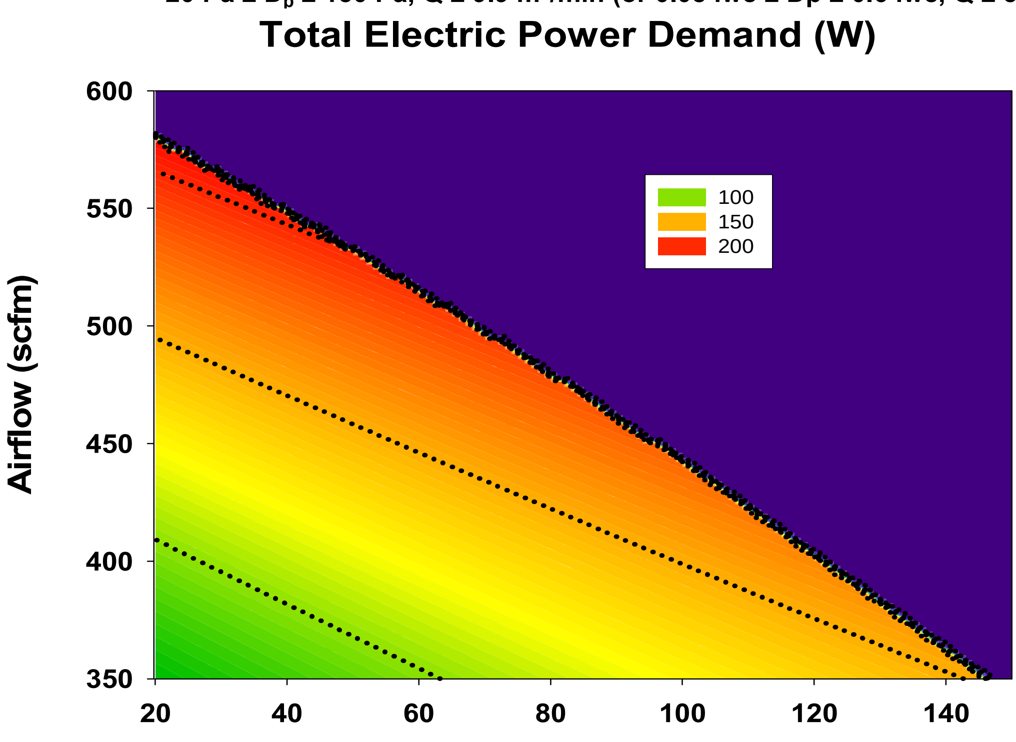
where

D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

$C_0 =$	1.16E+01
$C_1 =$	2.92E-01
$C_2 =$	-1.34E-01
$C_{11} =$	-1.35E-04
$C_{12} =$	1.04E-03
$C_{22} =$	7.70E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



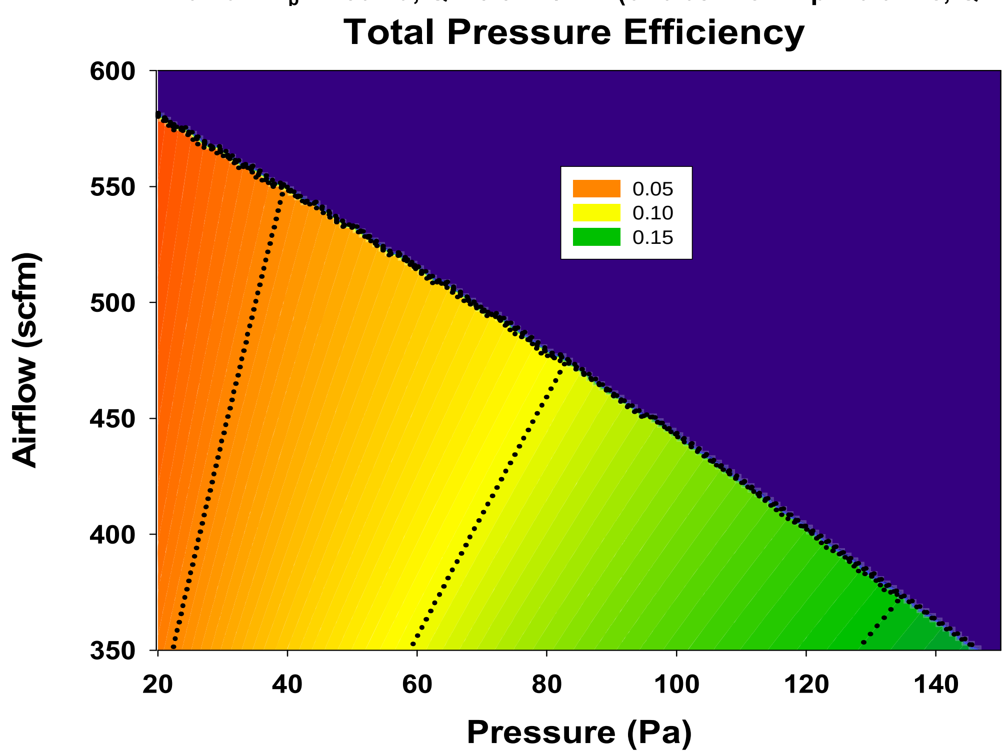
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:

1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-16

Prepared by

Tengfang Xu and Duo Wang

Environmental Energy Technologies Division

Lawrence Berkeley National Laboratory

September 18, 2006

Disclaimer

Acknowledgements

The project is funded by the California Energy Commission's Industrial section of the Public Interest Energy Research (PIER) program. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State, and Community Programs, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-16

Reporting Characteristics of the Unit Based on Manufacturer's Shipment
Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

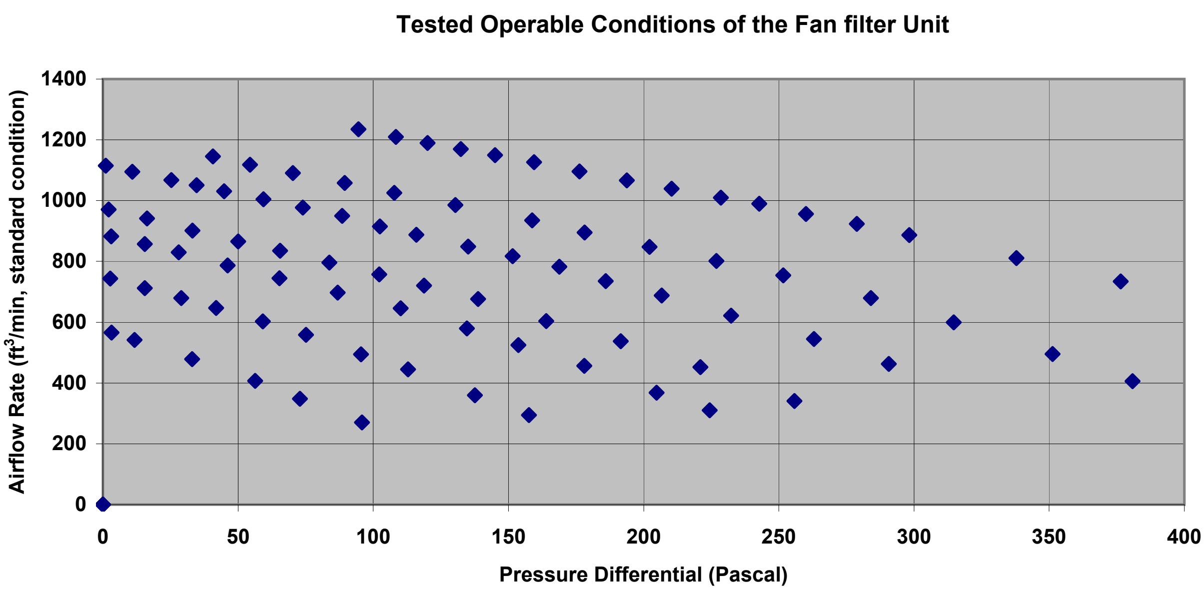
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electric power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electric power demand can be calculated using the following equation.

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Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

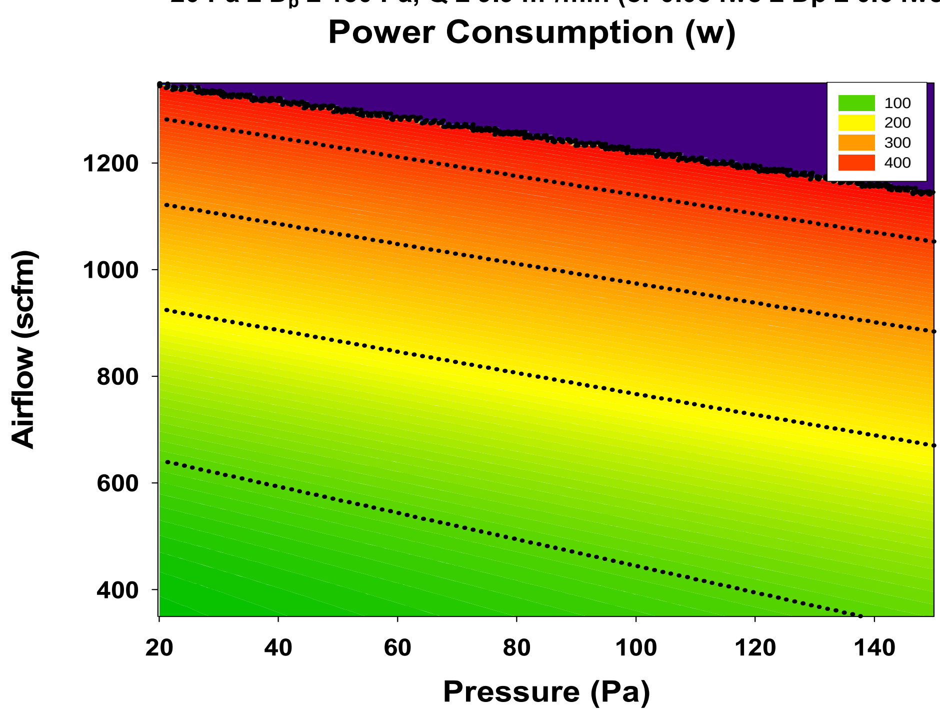
R^2 = 0.999

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

C_0 =	6.68E+01
C_1 =	2.22E-02
C_2 =	-1.76E-01
C_{11} =	3.75E-04
C_{12} =	9.34E-04
C_{22} =	3.24E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Total Pressure Efficiency

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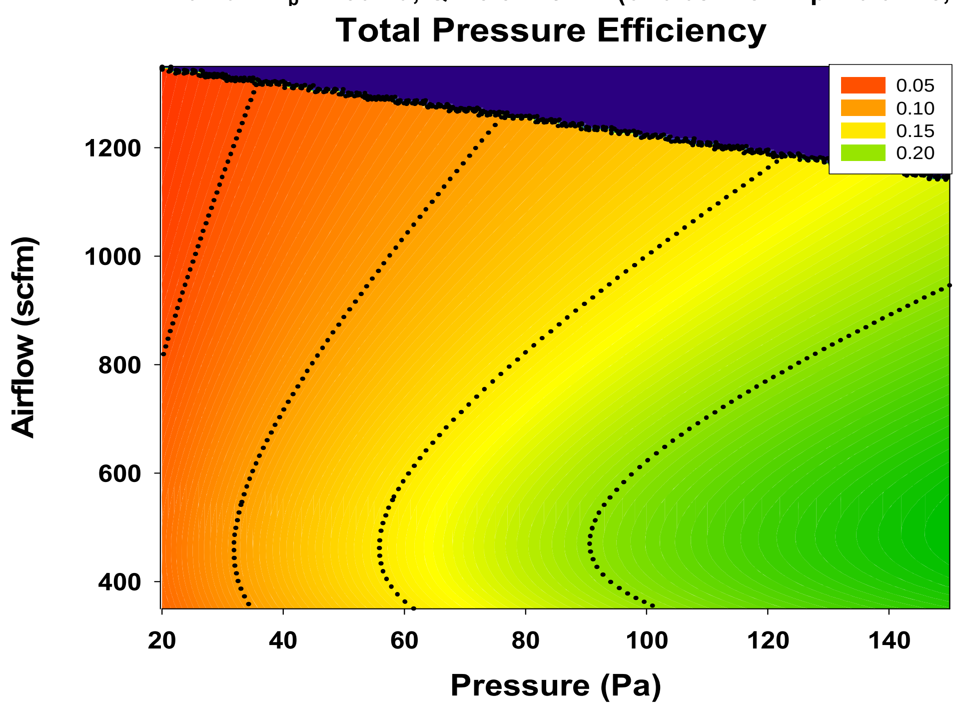
Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion: 1 kPa = 4.015 inch water column
1 m/s = 196.9 feet per minute (fpm)
1 m^3/min = 35.3 ft^3/minute (cfm)

Report on

Laboratory Evaluation of Fan-filter Unit

LBNL Report, LBID-2588-17

Prepared by

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Disclaimer

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Report on Laboratory Evaluation of Fan Filter Unit
Lawrence Berkeley National Laboratory, LBID-2588-17

Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer
Brand/Model
Serial Number
Unit Size
Fan Motor
Fan Wheel

Filter Efficiency

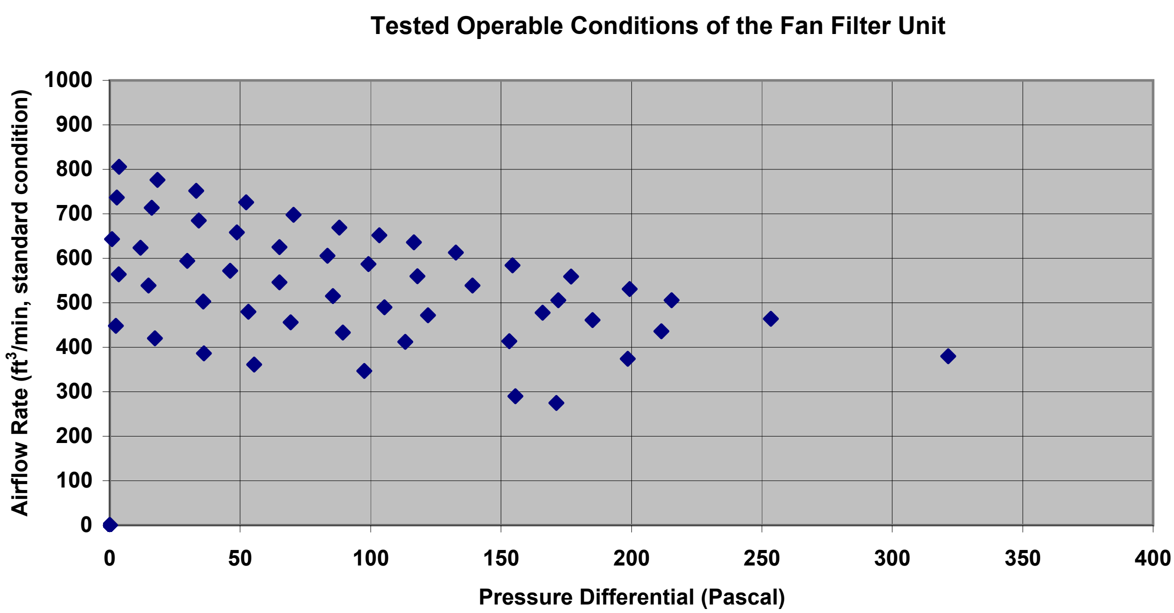
LBNL Tracking #

Reporting Energy Performance Based on Laboratory Testing

This report is based upon the laboratory evaluation of energy and airflow characteristics of the fan filter unit that was supplied to Lawrence Berkeley National Laboratory. All measured parameters, when applicable, are converted to their equivalents at the standard atmospheric condition (1 ATM, 20°C, sea level).

Total electric power demand, airflow rates, and pressure differential across the fan filter unit was recorded for a range of operable conditions of the unit. Normally, test conditions were selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under standard condition. The speed controller was set at its highest setting followed by lower setting. Figure 1 shows operable conditions that were tested with various speed control setting.

Figure 1. Operable conditions with various speed control setting



Total Electric Power Demand

Total electric power demand (EPD) of the fan filter unit includes all the electric power necessary to operate the fan filter unit. It was measured concurrently with airflow rates and pressures under all testing conditions. As a result, the total electric power demand can be calculated using the following equation.

The equation is derived from laboratory testing results from the operating conditions as shown in Figure 1. The R-square of the regression is included, which explains the statistical significance of the power demand predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of confidence in the power demand value derived from the laboratory testing.

Figures 2 illustrates the magnitude of total electric power demand within a selected range of operating conditions.

Electric Power Demand (Watt) = $C_0 + C_1 \times D_p + C_2 \times Q + C_{11} \times D_p^2 + C_{12} \times D_p \times Q + C_{22} \times Q^2$

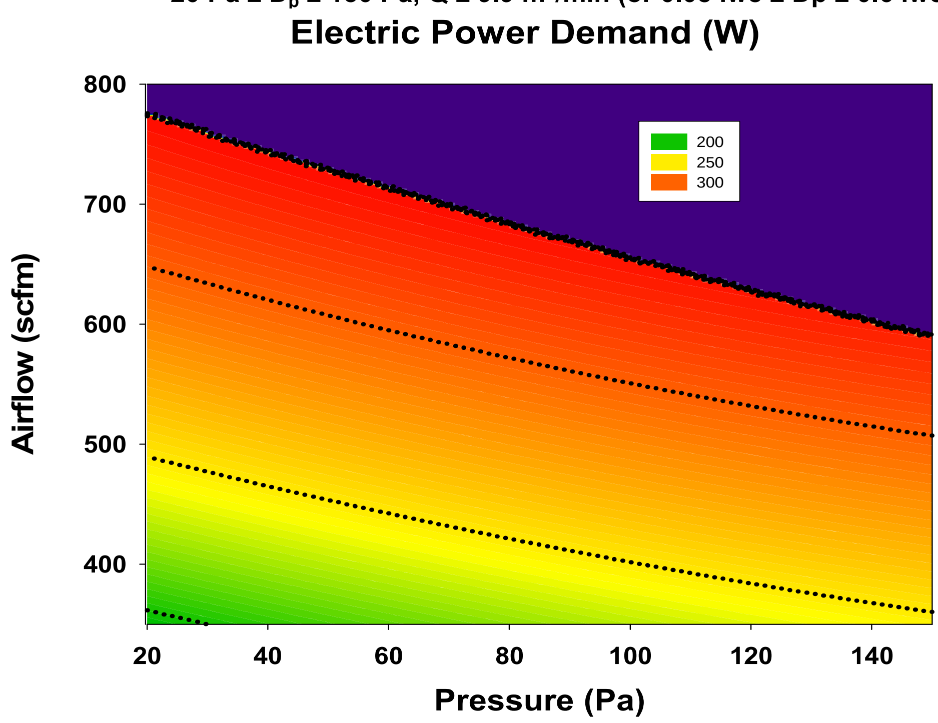
$R^2 =$ **0.999**

where D_p is the pressure differential across the fan filter unit, in Pascal

Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)

$C_0 =$	-1.04E+00
$C_1 =$	6.61E-01
$C_2 =$	6.23E-01
$C_{11} =$	-8.46E-04
$C_{12} =$	-3.56E-04
$C_{22} =$	-2.65E-04

Figure 2 Total electric power demand of the fan filter unit under selected operable conditions:
$20 \text{ Pa} \le D_p \le 150 \text{ Pa}$, $Q \ge 9.9 \text{ m}^3/\text{min}$ (or $0.08 \text{ iwc} \le Dp \le 0.6 \text{ iwc}$, $Q \ge 350$ scfm)



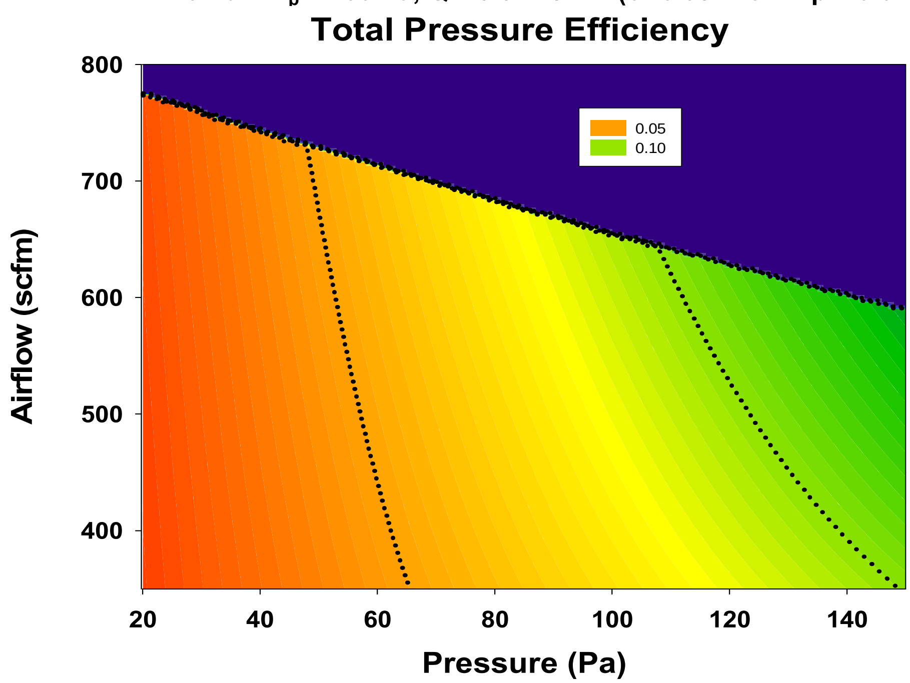
Total Pressure Efficiency

Total Pressure Efficiiency (TPE) is calculated by multiplying airflow rate and pressure differential across the unit then divided by total electric power demand as shown in the following equation.
Figures 3 illustrates the magnitude of total pressure efficiency within a selected range of operating conditions.

Total Pressure Efficiency (%) = 0.000471947443 x Q x D_p / EPD

where	Q	is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute)
	D_p	is the pressure differential across the fan filter unit, in Pascal
	EPD	is the total electirc power demand (EPD) of the fan filter unit include all the electric power necessary to operate the fan filter unit, in Watt

Figure 3 Total pressure efficiency of the fan filter unit under selected operable conditions: 20 Pa ≤ D_p ≤ 150 Pa, Q ≥ 9.9 m^3/min (or 0.08 iwc ≤ Dp ≤ 0.6 iwc, Q ≥ 350 scfm)



Note of unit conversion:	1 kPa = 4.015 inch water column
	1 m/s = 196.9 feet per minute (fpm)
	1 m^3/min = 35.3 ft^3/minute (cfm)