Standard Methods of Characterizing Performance of Fan Filter Units

Version 3.0, LBNL-62118

January 2007

Tengfang Xu
Lawrence Berkeley National Laboratory

Foreword

This publication is an update of the draft standard laboratory method previously developed and published to evaluate fan-filter-unit (FFU) operation.[1]

This updated document includes the newly refined standard laboratory method, with the addition of test procedures, modeling methods, and a reporting form to characterize the functionality, operation, and control of individual fan filter units. The standard methods benefit from a review of open literature on relevant industrial and international standards, recommended practices, publications, and guidelines.[2][3][4][5] [6][7][8][9][10][11][12][13][14][15] This new document builds upon past work, and integrates new knowledge gained from the experiments that were designed and conducted at Lawrence Berkeley National Laboratory (LBNL).

In addition to the laboratory method, test procedures, modeling methods, this document includes performance metrics for use of fully characterizing dynamic operation of an individual fan filter unit. The methods have been assessed and used to characterize a variety of fan-filter units made in Asia, Europe, and North America.[16][17][18][19][20] [21] [22] It is the intent of this document to provide technical specifics about the laboratory method, equipment requirements, test procedures, and modeling methods in order to fully characterize dynamic operation of individual fan-filter units.

A substantial portion of this document has been accepted and integrated in the working draft document titled “IEST Recommended Practice CC036.1: Testing Fan Filter Unit,” which is under the auspices of a technical Working Group within the Institute of Environmental Sciences and Technology (IEST). Founded in 1953, IEST is an ANSI-accredited standard-developing organization; Secretariat of ISO/TC 209 Cleanrooms and associated controlled environments; Administrator of the ANSI-accredited US TAG to ISO/TC 209; Administrator of the ANSI-accredited US TAG to ISO/TC 142 Cleaning equipment for air and other gases; and a founding member of the ANSI-accredited US TAG to ISO/TC 229 Nanotechnologies. The official industry standard – “IEST Recommended Practice CC036.1: Testing Fan Filter Unit” is under active development.

Disclaimer

Acknowledgement

The author wishes to thank Paul Roggensack, Anthony Wong, and Pramod Kulkarni of California Energy Commission for their support for the project. 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.

Contents

Standard Methods of Characterizing Performance of Fan Filter Units *1*
Version 3.0, LBNL-62118 ..... *1*
January 2007 ..... *1*
Disclaimer *2*
Acknowledgement *2*
1. Purpose *4*
  1.1 Intent **4**
  1.2 Review and Amendment **4**
2. Scope *4*
3. Nomenclature and Definition *6*
4. Setup, Instrumentation, Control, Method, and Procedure *7*
  4.1 Setup **7**
  4.2 Instrumentation **10**
  4.3 Control **13**
  4.4 Method **14**
  4.5 Procedure **15**
5. Performance Metrics and Calculation *17*
  5.1 Performance Metrics **17**
  5.2 Calculation **17**
6. Reporting *20*
  6.1 Descriptive Parameters **20**
  6.2 Test Conditions **20**
  6.3 Reporting Requirements and Format **21**
7. References *22*
8. Other Bibliography *24*
9. Addendum *25*
  9.1 Non-energy Performance **25**
  9.2 Airflow Uniformity **25**
  9.3 Interpretation of Results **25**
  9.4 Report Template **26**

1. Purpose

The purpose of this document is to provide a refined standard test method, test procedures, and modeling methods for laboratory characterization of dynamic fan-filter unit (FFU) operation with various control schemes. The methods are used to quantify unit's airflow rate, pressure differential, total electric power demand, and total pressure efficiency under various operation conditions. The refined methods provide a standard way to characterize dynamic operation of FFUs and to report their energy and airflow dynamics performance.

This stand-alone document may be referenced by and integrated into a relevant industry recommended practice or standard, e.g., the Recommended Practice (RP) being developed by the ANSI-accredited Institute of Environmental Sciences and Technology (IEST) – "IEST RP CC 036.1: Testing Fan Filter Unit."

1.1 Intent

This document is for anyone's use, including FFU manufacturers, end users, designers, researchers, and other interested parties such as utility companies and testing services companies. It is the intent of this document to provide technical specifics about the laboratory method, recommended equipment, test procedures, and modeling methods to characterize dynamic operation of individual fan-filter units under various conditions.

This document provides a first-ever means of fully characterizing FFU operation in laboratory setting, including functionality and energy efficiency. It is not the intent of this document to guide in-situ testing, although some of the techniques may be applicable to in-situ characterization.

1.2 Review and Amendment

This document is an update of the draft standard laboratory method previously developed for testing fan-filter units.[1] The updated document benefits from a literature review of relevant industrial and international standards and publications,[2][3][4][5] [6][7][8][9] [10][11][12][13][14][15] and builds upon new knowledge gained from substantial experiments that were designed and conducted at LBNL in order to improve its robustness. The new laboratory method, test procedure, and modeling method have been assessed and used to characterize dynamic operation of a variety of FFUs made in Asia, Europe, and North America.[16][17][18][19][20] [21] [22]

This document is subject to further review and amendment as experience in its use and technologies advance.

2. Scope

This document includes terminology used in the filter and cleanroom industry, and provides guidance specifically to quantify energy and airflow dynamics performance of fan-filter units under various operation and control schemes. The use of the document is limited to characterizing FFUs with filter media for removing particulates under normal cleanroom environmental conditions. This document does not cover filters used for controlling airborne molecular contamination (AMC). Users of FFUs dealing with AMC should refer to relevant documents for more information. The protocols in this document may be applicable for fan-filter units of various sizes, although additional experimental validation may be necessary.

Additional relevant standards and codes may be applicable to the construction and installation of FFUs. The standards or codes not addressed in this document may be made as part of the agreement between the customer and supplier. In addition, this document does not cover testing procedures for the following:

- Acoustic performance
- Vibration performance
- Particulate filtration efficiency
- Airborne molecular contamination filter media

The methods in this document may be used in development of a more comprehensive standard such as the Recommended Practice being developed by the ANSI-accredited Institute of Environmental Sciences and Technology (IEST).

3. Nomenclature and Definition

- **Q (Unit Airflow Rate):** Actual airflow rate through the FFU tested under a specific pressure differential across the unit, in cubic meter per second (m^3s^{-1}), liter per second (Ls^{-1}), cubic meter per minute (m^3min^{-1}), or cubic foot per minute (cfm).

- **p_{stat} (Static Pressure),** in Pascal (Pa) or inch water column (iwc).

- **p_{total} (Total Pressure):** Sum of the static pressure and the velocity pressure at a given location, in Pascal (Pa) or inch water column (iwc).

- **D_h (Hydraulic Diameter)** of a rectangular duct, in meter (m) or foot (ft), is defined as $D_h = \frac{2ab}{a+b}$, where a, b is the widths of the duct section.

- **ΔP_t (Total Pressure Differential):** Air pressure differential across the FFU corresponding to certain airflow rates and operating condition of the unit, in Pascal (Pa) or inch water column (iwc). This is defined as the difference between total pressures across the unit, i.e. $\Delta P_t = (p_{total-1} - p_{total-2})$. In FFU's application, it is often equivalent to the difference between static pressures across the unit, i.e., $\Delta P_t \approx (p_{stat-1} - p_{stat-2})$.

- **V (Airflow Speed):** Unit airflow rate divided by the net FFU face area under a specific static pressure differential across the unit, in meter per second (m/s) or foot per minute (fpm).

- **V_n (Nominal Airflow Speed):** Unit airflow rate divided by the gross FFU face area under a specific static pressure differential across the unit, in m/s or fpm.

- **Fan Wheel Rotational Speed**: Number of fan-wheel rotations per minute (RPM).

- **W_t (Total Electric Power Demand):** Total electric power input to operate the FFU at certain airflow conditions, including fan motor, controller, and transformer when applicable, in kW or HP.

- **P_t (Airflow Pressure Power):** The total pressure power of the airflow through an FFU,

  $\mathbf{P_t = Q \cdot \Delta P}$, in kW or HP.

- **η_t (Total Pressure Efficiency):** Ratio of airflow pressure power to the total power input to an FFU,

  $\eta_t = \frac{P_t}{W_t} = \frac{Q \cdot \Delta P_t}{W_t}$, dimensionless.

- **EPI (Energy Performance Index):** Unit's total electric power demand normalized by the airflow rate of an FFU,

$$EPI = \frac{W_t}{Q}\text{, in W/ (m}^3\text{h}^{-1}\text{) or W/cfm.}$$

4. Test Setup, Instrumentation, Control, Method, and Procedure

In order to characterize the dynamic operation of an individual FFU and report its performance data, it is necessary to conduct laboratory testing using consistent methods. The laboratory data may then be used to characterize FFU dynamic operation, and to provide energy performance reporting for FFUs with HEPA/ULPA filters in a consistent format. This document includes laboratory test method, test procedure, and modeling method to characterize operation of an FFU, and suggests performance metrics for reporting.

This section outlines test setup, instrumentation, control, method, and procedure recommended for the standard laboratory test.

4.1 Setup

The recommended standard tests include accurate measurements of total electric power demand, airflow rates (or actual airflow speeds), and the static (and total) pressure differential across the unit. In principle, measuring and characterizing FFU performance shall cover representative operation conditions. The test rig should be designed and set up to allow variations of achievable operation conditions as defined by the combination of controllable airflow rates and pressure differential across the unit. The setup should provide controllability of dynamic operation within the unit's operable range. The setup shall ensure minimal air leaks between the enclosed testing rig and its ambient space.

Figure 1 and Figure 2 illustrate a conceptual test setup and general layout for measuring airflow rate, static (and total) pressure, and total electric power demand. The unit's airflow rate (or airflow speed), pressure differential, and total electric power demand shall be concurrently recorded for various, achievable operating conditions. Each operating condition is determined by a combination of controllable pressure differential and airflow rate across the unit.

The airflow path may be designed as a flow-through into the FFU inlet (Figure 1) or a draw-through away from the FFU filter face in the test rig (Figure 2). For laboratory testing, an FFU may be mounted either horizontally or vertically on the exit of an airtight ductwork or chamber, or in the inlet of airtight ductwork leading to a chamber. For simplicity, the FFU is shown to be vertical in order to save requirements for additional space and material. However, placing the FFU in horizontal orientation may often be perceived to be desirable in order to emulate common FFU applications in cleanrooms, although the consequence of the unit's orientation is negligible.

For example in Figure 1, the conceptual setup shows that flow-nozzle(s) are used to measure airflow rate in the upstream of airflow path directed toward an FFU inlet. In the flow-through layout, airflow from immediate downstream of the FFU filter face can be discharged to the atmosphere or a space with a specific air pressure. The airflow measurement setup contains a single- nozzle (or multiple-nozzle bank when necessary) flow meter for recording airflow rates through the tested unit. Measuring the airflow rate using this type of flow meter test rig, which is consistent with ASHRAE/AMCA standard, may provide most accurate, NIST-traceable airflow rate measurement.

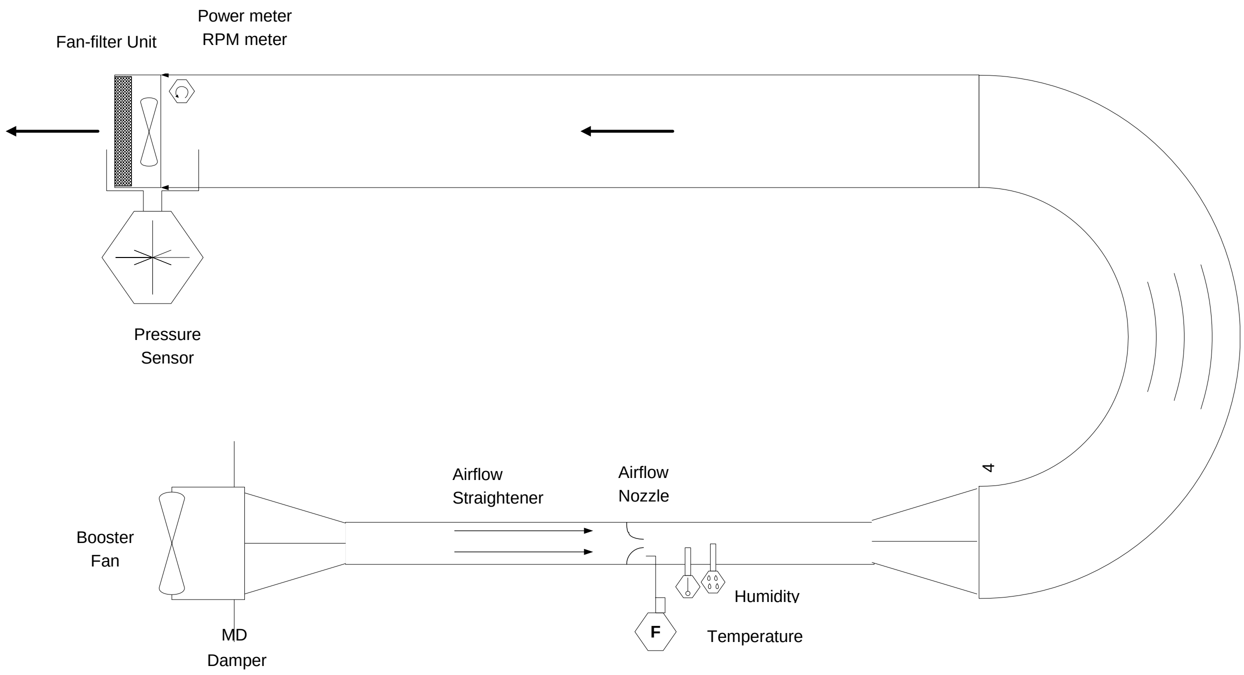

Figure 1 FFU test setup: flow-through setup

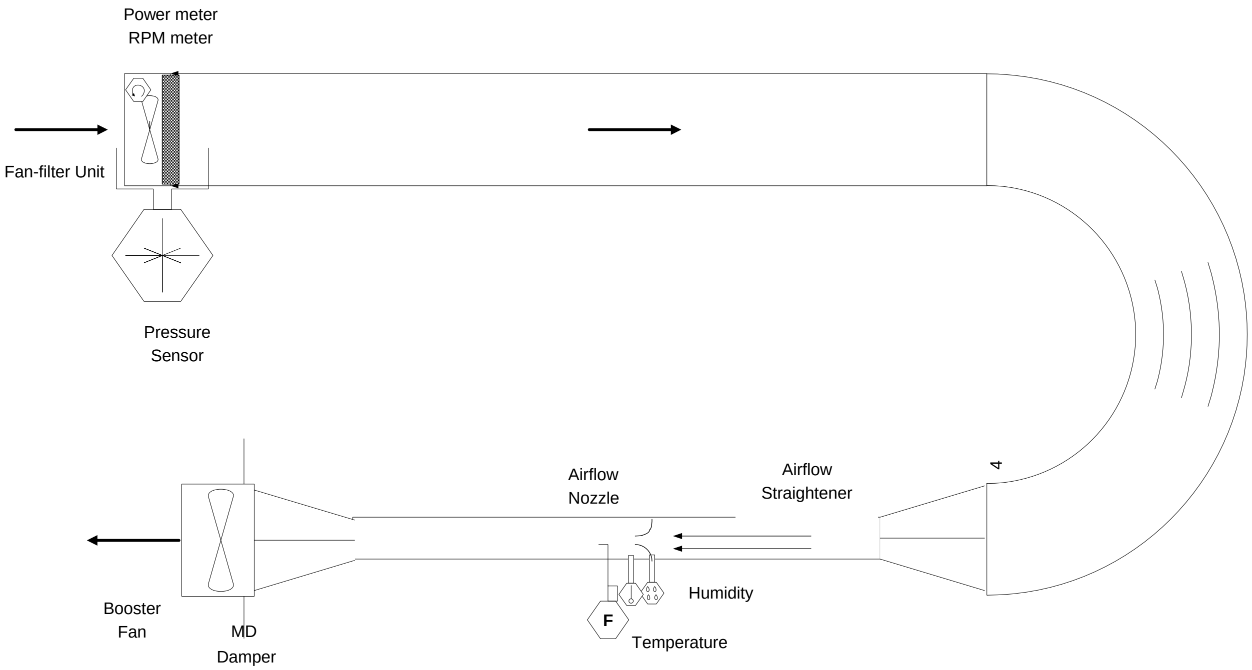

Figure 2 FFU test setup: draw-through

4.1.1 Principle

The laboratory measurement and evaluation of an FFU shall include testing a range of various operation conditions in order to characterize representative operation of the unit. The airflow rate and pressure differential through the unit shall be controllable within an operable range for the unit.

4.1.2 Test rig material, size, and sensor location

4.1.2.1 Material

Rigid ductwork or chamber is required for the test rig. Avoid using flexible or fire-prone material for ductwork.

4.1.2.2 Size of ductwork connected to FFU

The actual section size of ductwork mounted to the FFU shall be equal or greater than the unit section size.

In the setup illustrated in Figure 1 where FFU discharges the airflow to an unrestricted space, the recommended length of straight duct upstream of FFU may be two times (or more) of hydraulic diameter of the ductwork. Hydraulic diameter of a rectangular duct can be calculated as

$D_h = \frac{2ab}{a+b}$, where a, b is the widths of the ductwork section.

In the setup illustrated in Figure 2 where there is no flow restriction toward the inlet of the FFU, the recommended minimum length of straight duct downstream the FFU may be two times or more of hydraulic diameter of the ductwork.

4.1.2.3 Sizes of duct work connected to flow nozzle

The diameter of the round ducts upstream and downstream of the flow meter containing a flow nozzle should be the same as that of the flow meter. In addition to a flow nozzle, the flow meter may often contain a flow straightener. Pending requirements for airflow uniformity in the flow nozzle, the recommended minimum length of straight round duct upstream of the flow meter may be two times or less of the diameter of the flow nozzle, while minimum length of straight duct downstream of the flow meter may be up to five times of the diameter of the flow nozzle. The required minimal lengths of straight round ducts connected to upstream and downstream of the flow meter may also be determined by the requirements supplied by the flow-nozzle manufacturers, or the users may also refer to applicable ISO Standards.

4.1.2.4 Sensor location

The sensor for measuring airflow rates through the unit may be located upstream or downstream of the FFU, as illustrated in Figure 1 and Figure 2, respectively. Figure 1 represents the airflow in flow-through setting, and Figure 2 represents the airflow in draw-through setting.

A minimum of one static pressure tap should be installed at the center of 30-cm (1-foot) section upstream of the unit inlet for the flow-through setting (Figure 1), or at the center of 30-cm (1-foot) section downstream of the unit outlet for the draw-through setting (Figure 2). Additional pressure taps may be placed inside the ductwork or chamber to record airflow pressures along the ductwork.

An RPM sensor, when desired, shall be installed at a fixed location upstream of the unit's inlet. The selected location should allow the sensor to face the fan-wheel blades to monitor the rotating speeds of the fan-wheel blades. A trial test may be needed to ensure that the sensor can receive right signals from the rotating fan-wheel blades.

It is recommended that the measurements be conducted under normal surrounding air temperatures, iso-thermal conditions, and in steady-state airflow conditions. Sensors used to record atmospheric pressures, surrounding air temperature and humidity should be placed at locations that represent the psychometric conditions of the air flowing in and out of the test rig.

4.1.2.5 Air leakage

The equipment setup and configuration shall ensure minimal air leaks between the enclosed testing system and the ambient environment (external to test rig). The duct leakage including all traverse joints, longitudinal seams, and duct wall penetrations created for wire or cable connections should be sealed using appropriate sealants.

Maximum allowable air leakage should be controlled within less than 3% of airflow rates, otherwise appropriate measures shall be taken to minimize the effect of leakage on actual airflow rates. Such measure may include one or both of the following: 1) sealing the leak; 2) correcting the airflow rates by subtracting the leakage from measured airflow rate.

Section 4.4 includes a method of quantifying air leakage under various internal air pressures.

4.2 Instrumentation

The following enlists key instrumentation and required accuracies.

4.2.1 Airflow rate meter

The measurement of airflow rates through the FFU may be conducted upstream or downstream of the FFU, with a measurement uncertainty within ±5%.

The recommended range of the airflow rates for testing depends on the actual section size of the fan filter unit. Flow nozzles of multi-sizes may be necessary to ensure measurement accuracies. For example, airflow meters with acceptable accuracies should be selected and used to measure airflow rates ranging from 300 cfm up to 1,200 cfm or higher for a 61-cm-by-122-cm unit (or 2-foot-by-4-foot unit); while bigger airflow meters with acceptable accuracies should be selected and used to measure airflow rates from 600 cfm up to 2,400 cfm or higher for 122-cm-by-122-cm units (or 4-foot-by-4-foot units).

Acceptable airflow meters must be nozzle-based airflow meters [1] [8] or applicable airflow meters that conform to ISO Standard 5167 series.[5] The flow meter may include a flow straightener and converging nozzle(s), with a Pitot-static type sensor centered at the outlet of the flow nozzle. Calibrations and validation must be carried out to ensure accuracies are satisfactory. Additional flow nozzles or straightener may be necessary, pending requirements for the selected airflow nozzle(s) and actual airflow rates. For example, for 61-cm by 122-cm (2x4') fan filter units, using Brandt Model NZP1031-10"-1-CF flow meters may measure airflow rates from 250 to 1300 cfm (7 to 37 m^3min^{-1}), corresponding to pressure signals ranging from 15 to 415 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.

For fan-filter units with smaller or larger sizes (e.g., 61-cm x 61-cm or 122-cmx122-cm), nozzle(s) with smaller diameters or with larger diameters shall be considered to use in order to obtain accurate measurements of airflow rates that correspond to the actual operating range of the fan-filter unit. Normally, smaller fan-filter units would require flow nozzles with smaller diameters so that required accuracies can be maintained especially at lower airflow rates. Uncertainty analysis should be performed when selecting flow nozzles.

4.2.2 Pressure transducer

Appropriate pressure transducers should be used to measure or monitor airflow rates and air pressures in various locations in the test rig.

4.2.2.1 Pressure transducer(s) with sufficient accuracies shall be used with the airflow meter to measure and record airflow rates through the flow nozzle(s).

4.2.2.2 Pressure transducer(s) with sufficient accuracies shall be used to measure and record pressure differential before and after of the fan-filter unit. Pressure differential across the unit shall be recorded for each of the operating conditions. The types of pressure transducers may include Pitot Tubes sensors.

The output signals of pressure transducers may be recorded using a computer-based data acquisition system. For example, a multi-channel electronic differential pressure transducer with measuring range of ± 400 Pa, rated accuracies of the larger of ± 0.2 Pa or ±1% of reading.

The calibration of the multi-channel pressure transducer system may be checked using a micro-manometer that has a micrometer and electrical circuit for precisely measuring the height of the fluid column. Users of micro-manometers may obtain measurements repeatable within 0.1 Pa.

4.2.3 Pressure tap

Static pressure taps should be installed at various locations in the ductwork or chamber to measure or monitor air pressures along the ductwork or chamber. The pressure taps may consist of Pitot tubes installed along the center of sections of the ductwork leading to the fan-filter unit.

Additional pressure taps may be installed around and inside the fan-filter unit's internal housing to measure the profile of air pressures. Such pressures taps should be located at as many locations as possible and their sizes should be sufficiently small so that they do not obviously change the airflow patterns or air pressure distribution of the internal space of an FFU. Such pressure taps may consist of numerous tiny holes that can be connected together (such as the ones in a soaker hose) to represent magnitudes of air pressure within the space.

Adjustment of airflow rates under a certain fan-wheel speed setting may be achieved by a combination of the following: 1) varying the set points of fan-wheel speeds of the FFU when applicable; 2) varying fan-wheel speeds of the booster fan thereby changing airflow rates, and 3) controlling the pressure drop across the airflow damper whose position affects the pressure loss as a way to emulate the changing pressure resistance in the external system. Usually, a combination of simultaneously varying fan-wheel speeds of the booster fan and controlling the pressure drop across the damper may adjust actual airflow rates through the unit.

4.2.4 Barometer

A barometer should be used to record the atmospheric pressure around the test rig. Normally, a portable barometer with digital display may be used to measure the atmospheric pressure.

4.2.5 Electric power meter

Total electric power demand shall be measured using an accurate electric power meter. The measurement and recording of electric power demand should be performed concurrently with airflow rate and pressure measurement. Pending the types of power supply requirements (e.g., AC vs. DC power, one-phase vs. three-phase AC power), an appropriate power meter should be used to measure true power demand of the unit. The measurement output of true mean electric power demand for the whole unit would be the total power supply to the fan motor, speed control and display device, transformer, and additional accessories. The output of the measurements shall include true mean electric power demand, and may include voltage, current, frequency, and power factor.

The selected power meter may be calibrated with an accurate power meter, which should be accurate with distorted waveforms and poor power factors.

4.2.6 Fan-wheel speed meter

The fan-wheel speeds of the FFU may be measured using a device for recording number of rotations per minute (RPM) concurrently with other measurements for each of the test conditions. If desired, an RPM sensor would be used along with necessary accessories such as reflective tape or color coating. Before being used, the RPM meter should be calibrated and be NIST-Traceable, e.g., measuring 500 RPM – 3,000 RPM with one or multiple pulses per revolution.

4.2.7 Data logger(s) and data acquisition

Data logger(s) may be used to record measured parameters including airflow rate, air pressure, temperature, humidity, and electric power demand for each of the testing conditions. Recommended data logger(s) to serve this purpose include multi-channel electronic data loggers with signal input of temperature, pressure, humidity, and electric power from transducers or sensors.

The output signals of data loggers, such as airflow rate and pressure differential, air temperature and humidity may be recorded with a computer-based data acquisition system.

4.3 Control

In order to control the airflow rate and pressure differential across the FFU while characterizing dynamic operation of an FFU within its operable range, an ancillary fan and a damper are often installed to modulate the pressure differential and airflow rate across the FFU. The ancillary fan is used to booster the test rig's capability to emulate various external resistances. Such a booster fan may include a variable-speed controller to adjust the airflow rates through the fan.

Individual FFUs may come with different control device or schemes for adjusting fan-wheel speeds, airflow rates and pressure differentials across the units. Two common control schemes are described in the following. For each of the control schemes, different operation set points are recommended for laboratory testing in order to characterize dynamic operation of the FFU.

4.3.1 FFU with a single-speed-drive motor

An FFU that comes with a single-speed-drive motor does not have any speed controller used to control its fan-wheel rotational speed. The FFU shall be tested at various operating conditions by adjusting damper positions and booster fan's speed setting. The adjustment of damper positions and booster fan's speeds modulates the pressure differential and airflow rate across the FFU. The corresponding air pressure differential, unit airflow rate (and airflow speed), and total electric power demand shall be recorded.

4.3.2 FFU with a multi-speed-drive motor

An FFU that comes with a multi-speed-drive motor offers the ability to operate the unit at various preset fan-wheel rotational speeds. When applicable, the unit should be tested for each preset level of the fan-wheel's rotational speed setting. At each level, adjusting damper positions and booster-fan's speeds modulates the pressure differential and airflow rate across the unit. The corresponding pressure differential, unit airflow rate (and airflow speed), and total electric power demand shall be recorded for operating conditions selected.

4.3.3 FFU with a variable-speed-drive (VSD) motor

For an FFU equipped with speed modulation device using a VSD motor, the unit should be tested at selected levels of fan-wheel's rotational speeds under operable conditions. Similar to the FFU with multi-speed-drive motor, the corresponding pressure differential, unit airflow rate (and airflow speed), and total electric power demand shall be recorded for each selected level of fan-wheel's rotational speeds, for example, 10%, 30%, 50%, 70%, 90%, and 100% of its maximal RPM.

4.4 Method

The unit airflow rate, pressure differential across the FFU, and total electric power demand shall be recorded concurrently at any selected operating condition. The operating conditions selected for testing should represent typical operable conditions that the unit can achieve.

In order to generate various operable conditions, pressure differential across an FFU should be adjusted at various levels for each fan-wheel speed setting when applicable. For example, at each RPM setting, pressure differential can be set to be as low as zero to 0.2-inch water column (0-50 Pa) up to 1.5-inch water column (375 Pa), when applicable.

The total electric power demand and performance metrics measured and calculated for a specific operating condition, e.g., pressure differential of 0.5-inch water (125 Pa) coupled with an actual airflow rate of 520 cfm (245 Ls^{-1})) that the unit is capable of supplying.

4.4.1 Unit airflow rate measurement

Actual unit airflow rates (and/or airflow speeds) correspond to selected fan-wheel speeds and actual pressure differentials across the unit. The rate of airflow shall be measured at a steady state through a circular conduit by means of pressure differential device (orifice plates, nozzles, or Venturi tubes) that is inserted into the circular cross-section duct. In case of using orifice plates, the circular duct diameter should be more than 50-mm (2-inch) and less than 1000-mm (40-inch), and Reynolds numbers over 5,000. In the case of using nozzles and Venturi nozzles, the circular duct diameter should be more than 50-mm (2-inch) and less than 630-mm (25-in), and Reynolds numbers over 10,000. In the case of using Venturi tubes, the circular duct diameter should be more 50-mm (2-inch) and less than 1200-mm (47-inch), and duct Reynolds numbers are over 20,000. [5]

There are two options to obtain unit airflow rates: measuring the airflow rate using a calibrated pressure differential device (e.g., flow-nozzle), either upstream or downstream of the FFU[1][8][9].

4.4.2 Pressure differential across unit

Concurrent measurements of the static (or total) pressure differential across the FFU shall be recorded. In addition, concurrent pressure differential across the HEPA or ULPA filter may be measured.

4.4.3 Fan-wheel rotational speed

To test FFU at various, operable conditions, fan-wheel rotational speed – rotations per minute (RPM) if any should be adjusted whenever applicable. The fan wheel rotational speeds should be controlled and may be recorded concurrently with other parameters.

4.4.4 Power supply and total electric power demand

Total electric power demand of a fan filter unit includes all the electric power necessary to operate and control the fan filter unit. Total electric power demand shall include fan motor, speed control and display device, transformer, and additional accessories attached to the unit. Total electric power demand shall be measured concurrently for all representative operating conditions defined by airflow rates and actual static (total) pressure gain across the unit. Electric power measurement shall include true mean electric power, and may include voltage, electric current, and frequency.

4.4.5 Ambient conditions

Measured parameters and metrics in the experiment shall be converted and reported under the standard air condition. The test can be conducted at various ambient air conditions; however, the air temperature of the testing facility should be within a normal operating range to ensure that the fan motor performance would be minimally affected by surrounding air temperature. In addition, cautions must be taken to ensure that the airflows through the testing device are isothermal. Otherwise, necessary corrections shall be undertaken for reporting to account for effects on the measured data.

The ambient air conditions (e.g., atmospheric pressure, temperature, and humidity) shall be recorded. The recorded data (elevation, temperature, and humidity) shall be used for the air density conversion to the equivalent standard condition (i.e., 1 atm, 20°C).

4.4.6 Air leakage in test rig

The equipment setup and configuration shall ensure minimal air leaks between the enclosed testing system and the ambient environment (external to test rig)[17]. Measures to reduce leakage of test rig should be carried out to ensure leakage ratio is at a minimal level for representative operating conditions.

The air leakage can be quantified by performing the following 1) sealing the test rig (including FFU when necessary), 2) connecting an airflow meter coupled with a booster fan, 3) measuring leaking airflow rates corresponding to various air pressure differential across the ductwork. The measured airflow rates corresponding to certain pressure differential can then be used to quantify airflow leakage ratio, defined as leaking airflow rate divided by the total airflow rate at certain pressure inside the test rig.

4.5 Procedure

In addition to specific requirements for the test rig, measurement device, sensors, and data acquisition, the following provides an overall test procedure. The procedure enlists key steps before, during, and after a laboratory test.

- Perform calibration of measurement equipment and ensure all devices are working properly.

- Take necessary measures to eliminate or minimize air leakage in the test rig including ductwork so that the measured airflow rate through the flow nozzle would accurately represents the airflow rate through the FFU. If necessary, perform air leakage test of test rig system, with the open-end of the ductwork sealed.

- If desired, install an RPM meter to monitor the fan-wheel speeds of the FFU in the test rig.

- Install pressure taps in and around FFU when necessary.
- Connect wiring for all instrumentation and data acquisition system, which may include pressures, flow meter, power meter, RPM meters, temperature, humidity, etc.
- Install the FFU to be tested, then perform air leakage test of test rig system with the FFU installed and all open-ends sealed when necessary.
- Record ambient-air conditions, including temperature, humidity, and atmospheric pressure.
- Design and install a guiding tool used for externally adjusting setting of FFU's fan-wheel speed.
- Turn on FFU and then turn on the data acquisition system when applicable to show the trend of air temperature, pressure, airflow rate, and electric power demand versus time.
- Synchronize the time stamps for all data loggers and data acquisition when applicable. Save the data files.
- Before taking measurements, wait for the airflow and operation of test equipment to reach a steady state. The parameters to check for stabilization include airflow rate, pressure, electric power demand, and fan-wheel speed when applicable.
    - Normally continuous operation with a minimum of 30-minute should be required.
    - Longer waiting time may be necessary if the preset airflow rate, air pressure or temperature is considerably in a non-steady-state.
- Adjust and measure the airflow rate and pressure differential through the unit.
    - Set the unit's fan-wheel-speed setting at the maximal position.
    - Adjust the booster fan speed and the damper position to measure maximal airflow rate under the zero pressure differential condition (similar to a free-flow condition).
    - Then gradually adjust the setting of the booster fan speed and the damper position to reduce airflow rates while increasing the pressure differential. Take measurement at each preset operating condition.
    - Repeat the adjustment in steps, until a maximal pressure differential is achieved while airflow rate reaches it minimal. Take measurement at the preset operating condition.
    - Each recorded operating condition should be stabilized and maintained for at least three to five minutes. Record all parameters for each operating condition. Normally up to ten operating conditions should be recorded.

- When applicable, set down the unit's speed-control setting in steps from its maximum, e.g., by 10%, or a preset position. Repeat the above measurements and recording.
- When applicable, continue to set the unit's speed-control setting down from its last setting. Repeat the measurements and recording until the test at a minimal RPM setting is complete.
- Save the data files. Take additional notes when necessary.
- Record ambient-air conditions, including temperature, humidity, and atmospheric pressure.
- Convert and/or export the experimental data files to appropriate formats for calculations and analysis.
- Periodically examine device, test-rig integrity, and measurement accuracies. The experimenter should take notes of environmental parameters such as air temperature and air pressure, and shall note any uncommon observations concerning the test and performance data. Any incident that warrants validation of the test-rig integrity or device calibration should entail repeating the tests or performing additional tests.

5. Performance Metrics and Calculation

5.1 Performance Metrics

5.1.1 Unit airflow rates (or actual airflow speeds): corresponds to various pressure differential and fan-wheel-speed setting. The maximum unit airflow rate shall be reported.

5.1.2 Total electric power demand: corresponds to unit's airflow rates and pressure differential across the FFU. The total electric power demand can be measured and calculated for any operable condition - airflow rate (or actual airflow speed) with the actual pressure gain across the unit.

5.1.3 Total pressure efficiency: At a given operation condition defined by pressure differential and airflow rates, is a function of operating pressure differential and airflow rates. Total pressure efficiency may be measured and calculated for any operable condition.

5.1.4 Energy performance index (EPI): corresponds to various pressure differential and airflow rates. EPI can be measured and calculated for any operable condition. EPI may be reported directly based upon a selective pressure differential, e.g., 125 Pa (or 0.5-inch water). In addition, EPI can be reported for a specific unit airflow speed (e.g., 70 fpm) along with the actual pressure differential.

5.2 Calculation

Perform calculations and data conversion of the parameters listed in Section 4.4 and performance metrics in Section 5.1 including polynomial regression models described in the following:

5.2.1 Total electric power demand is characterize based upon laboratory test data, as it relates to operating conditions that are defined by unit airflow rates and pressure differential.

A) For FFUs with a single-speed drive, the total electric power demand can be calculated using either of the following equations.

$W_t = C_0 + C_1 \cdot D_p + C_2 \cdot D_p^2$, 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.

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

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

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.

The equations can be derived and used for predicting actual electric power demand.

The R-square of the regressions should be included, which explains the statistical significance of the power demand fitting predicted by the equation. A higher R-square number (with the possible maximum of 1) indicates higher degree of certainties in the power demand characterization derived from the laboratory testing.

5.2.2 Total pressure efficiency may be calculated based upon laboratory test data, as it relates to operating conditions that are defined by unit airflow rates and pressure differential. The following equations show the calculations:

A) For FFUs with a single-speed drive, the total electric power demand 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.

B) For FFUs with a multi-speed-drive, the total electric power demand 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.

The above equations can be used for predicting total pressure efficiency at any operable condition of the unit.

5.2.3 Energy performance index (EPI). An equation of calculating EPI maybe included if desired, but not essential. Energy performance index (EPI) may be calculated for any defined operating condition, as it is a function of unit airflow rates and pressure differential, using the following equations.

A) For FFUs with a single-speed drive, the energy performance index (EPI) can be calculated using either of the following equations.

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

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.

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

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

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.

The above equations can be used for predicting EPI at any operable condition of the unit.

6. Reporting

6.1 Descriptive Parameters

6.1.1 Physical size

The physical size, weight, noise, vibration, efficiencies, maintenance, capacity, and reliability of an FFU are among the major considerations of product design and selection. Physical dimensions (height, length, and width) of the fan filter unit and weight should be reported.

6.1.2 Filter characteristics

6.1.2.1 Filter type, material, and dimensions shall be reported. The net face area of the FFU should be reported when available.

6.1.2.2 Particulate filtration efficiency shall be specified, e.g., based upon the data information from filter supplier, e.g., 99.99% for 0.3-µm particles. Details of specifying acceptable filter testing standards may be found in relevant literatures, such as IEST Recommended Practices and/or ISO Standards.

6.1.2.3 Pressure resistance across the HEPA or ULPA filter may be reported to provide its performance with the change of airflow rates and RPMs.

6.1.3 Fan-wheel and fan motor

It is common that an FFU is equipped with backward inclined centrifugal impellers. The report may also include the type and size of the fan wheel and motor used in the FFU. For example, the parameters may include the following: impeller diameter, number of blades, and blade pitch, when such information is available.

An FFU may be equipped with an AC external rotor motor (single-phase or three-phase) or a DC external rotor motor. FFU motors are equipped with single-, multi-, or variable-speed-drive pending design and operation requirements. The latter two types allow on-field adjustment of fan wheel speeds of the unit. The option of adding an adjustable speed drive is to provide an easy means to adjust airflow rates in the field.

6.2 Test Conditions

6.2.1 Unit airflow rate

Actual unit airflow rate (and/or airflow speeds) shall be recorded corresponding to each selected operating condition- defined by pressure differential and airflow rate across the FFU.

6.2.2 Pressure differential across the FFU

To generate various testing conditions, the pressure differential across FFU shall be controlled at various levels for each RPM setting. For example, the pressure differential can be 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 can then be 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 specific actual unit airflow rate(s) that the unit is capable of supplying.

6.2.3 Fan-wheel rotational speed

To test FFU at various and operable conditions, fan-wheel rotational speed – rotations per minute (RPM) should be adjusted to cover its operable range. The fan wheel rotational speeds should be recorded when necessary.

6.2.4 Total electric power demand

Total electric power demand shall include the fan, frequency drive motor, speed control device, transformer when applicable, etc.

6.2.5 Ambient air

Recorded air conditions in the experiment shall be converted to standard air condition for calculating air density. The recorded data (elevation, pressure, temperature, and humidity) shall be used for the air density conversion to the equivalent standard condition (i.e., 1 atm, 20°C).

6.3 Reporting Requirements and Format

6.3.1 Descriptive parameters specified in Section 6.1 should be reported. For example, the report shall include specification of sizes of the fan-filter unit, and motor speed control for the operating conditions tested.

6.3.2 End users may require and specify parameters that need to be reported. These may include the performance metrics in Section 5.1.

6.3.3 Experimental data obtained through the testing shall be used to provide performance evaluation within the range of operating conditions tested.

6.3.3.1 The report shall contain information of the airflow rates, pressure differentials, total electric power demand, and total pressure efficiency.

6.3.3.2 Total electric power demand shall be reported using equations in Section 5.2.1, as it relates to operating conditions as function of unit airflow rates (or actual airflow speed) and pressure differential across the FFU. For example,

A) For FFUs with a single-speed drive, the total electric power demand shall be reported with equations in one of the following forms:

$W_t = C_0 + C_1 \text{ x } D_p + C_2 \text{ x } D_p^2$

$W_t = C_0 + C_1 \text{ x } Q + C_2 \text{ x } Q^2$

Where

D_p is the pressure differential across the fan filter unit.

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

B) For FFUs with a multi-speed-drive, the total electric power demand shall be reported with equations in one of the following forms:

$W_t = C_0 + C_1 \text{ x } D_p + C_2 \text{ x } Q + C_{11} \text{ x } D_p^2 + C_{12} \text{ x } D_p \text{ x } Q + C_{22} \text{ x } Q^2$

Where

D_p is the pressure differential across the fan filter unit
Q is the airflow rate across the unit under standard atmospheric condition.
The R-square of the regressions should be included.

6.3.3.3 Total pressure efficiency may be reported using equations in Section 5.2.2, as it relates to operating conditions as function of unit airflow rates and pressure differential.

6.3.3.4 Energy performance index may be reported using equations in Section 5.2.3, as it relates to operating conditions as function of unit airflow rates and pressure differential.

6.3.4 All experimental data reported shall be converted to the standard atmospheric condition.

7. References

[1] Xu, T. 2005. “Laboratory Method of Testing Energy Performance of Fan Filter Units, Version 1.3.” Berkeley National Laboratory Report LBNL-54626, Berkeley, California.

[2] International Organization for Standardization (ISO). 2002. ISO 14644-3 “Cleanrooms and associated controlled environments — Part 3: Metrology and test methods.” The Institute of Environmental Sciences and Technology (IEST). 5005 Newport Drive, Rolling Meadows, IL.

[3] International Organization for Standardization (ISO). 2001. ISO 14644-4 “Cleanrooms and associated controlled environments — Part 4: Design, Construction and Start-up.” The Institute of Environmental Sciences and Technology (IEST). 5005 Newport Drive, Rolling Meadows, IL.

[4] International Organization for Standardization (ISO). 2004. ISO 14644-7 “Cleanrooms and associated controlled environments — Part 7: Separative enclosures (clean air hoods, gloveboxes, isolators, minienvironments).” The Institute of Environmental Sciences and Technology (IEST). 5005 Newport Drive, Rolling Meadows, IL.

[5] 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.”

[6] The Institute of Environmental Sciences and Technology (IEST). 2004. IEST Handbook of Standards and Practices, Recommended Practice in Contamination Control, IEST-RP-CC002.2: “Unidirectional Flow Clean Air Devices.” 5005 Newport Drive, Rolling Meadows, IL.

[7] The Institute of Environmental Sciences and Technology (IEST). 2004. IEST Handbook of Standards and Practices, Recommended Practice in Contamination Control, “IEST-RP-CC006.3: Testing Cleanrooms.” ISBN: 1-877862-99-1. 5005 Newport Drive, Rolling Meadows, Illinois, USA

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

[9] ASHRAE. 1987. *ASHREA Standard 41.2 (RA 92)* - Standard Methods for Laboratory Airflow Measurements.

[10] ASHRAE Standard 25. Methods of Testing Forced Convection and Natural Convection Air Coolers for Refrigeration

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

[12] ASHRAE Standard 40: Methods of Testing for Rating Heat Operated Unitary Air Conditioning Equipment for Cooling

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

[14] ASHRAE Standard 48: Methods of Testing for Rating Air Conditioning and Packaged Terminal Air Conditioner Heating Capacity

[15] NEBB. 1996. Procedural Standards for Certified Testing of Cleanrooms, 2nd Edition 1996 - Chapter 5: Airflow Test Procedures.

[16] Xu, T. 2005. Advanced Efficient Filtration: Fan-filter Units. Final Report, Lawrence Berkeley National Laboratory Report, LBNL-57727, Berkeley, California.

[17] Xu, T. and D. Wang. 2007. "Demonstration of Advanced Filtration Technologies: Developing Energy-rebate Criteria through Performing Standard Laboratory Tests and Statistical Analyses." Lawrence Berkeley National Laboratory Report, LBNL-61684.

[18] Chen, J., C. Lan, M. Jeng, and T. Xu. 2007. "The Development of Fan Filter Unit with Flow Rate Feedback Control in a Cleanroom." *Building and Environment.* Lawrence Berkeley National Laboratory Report, LBNL-60530.

[19] Jeng, M., T. Xu, and C. Lan. 2004. "Toward Green Systems for Cleanrooms: Energy Efficient Fan-filter Units," *Proceedings of Semiconductor Equipment and Materials International Conference (SEMICON) West 2004* - SEMI Technical Symposium: Innovations in Semiconductor Manufacturing (STS: ISM), Pages 73-77, San Francisco, California, July 2004; Lawrence Berkeley National Laboratory Report LBNL-55039.

[20] Xu, T. and M. Jeng. 2004. "Laboratory Evaluation of Fan-filter Units' Aerodynamic and Energy Performance," *Journal of the IEST*, Volume 47: 116-120, Institute of Environmental Sciences and Technology (IEST), Illinois. Lawrence Berkeley National Laboratory Report LBNL-54250.

[21] Xu, T., C. Lan., and M. Jeng. 2007. "Performance of Large Fan Filter Units for Cleanroom Applications." *Building and Environment.* Lawrence Berkeley National Laboratory Report,

LBNL-58220.

[22] Xu, T. 2006. "Development of a Fan-Filter Unit Test Standard, Laboratory Validations, and its Applications across Industries." CleanRooms Magazine, November 2006, LBNL-61750

8. Other Bibliography

[23] The Institute of Environmental Sciences and Technology (IEST). 2005. IEST-RP-CC 001.4 - HEPA AND ULPA Filters. Rolling Meadows, IL.

[24] ASHRAE. 2003. ASHRASE Handbook - HVAC Applications: Chapter 16 - Clean Spaces.

[25] The Institute of Environmental Sciences and Technology (IEST). 1992. IEST-RP-CC007.1: Testing ULPA Filters. Rolling Meadows, IL.

[26] The Institute of Environmental Sciences and Technology (IEST). 1995. IEST-RP-CC021.1: Testing HEPA and ULPA Filter Media. Rolling Meadows, IL.

[27] The Institute of Environmental Sciences and Technology (IEST). 2005. IEST-RP-CC 034.2 - HEPA and ULPA Filter Leak Tests. Rolling Meadows, IL.

[28] The Institute of Environmental Sciences and Technology (IEST). IEST-RP-CC 035.1 - Design Considerations for Airborne Molecular Contamination Filtration Systems in Cleanrooms. Rolling Meadows, IL.

9. Addendum

Informative (not part of this standard test method)

9.1 Non-energy Performance

Methods of testing noise, particulate filtration efficiency, and filter leak have been addressed in specific industry standards or recommended practices. Although the measurements of these parameters are not covered in this procedure, FFU manufacturers should make this information available as part of the product specifications. Vibration and acoustic issues are important and need to be addressed; however, these are outside the scope of this document.

9.2 Airflow Uniformity

In addition to filtration performance, FFU's airflow uniformity is an important element to characterize the overall performance of the FFU with HEPA or ULPA filters; therefore, airflow uniformity is normally required for cleanroom certification, and may be part of the product specification.

Airflow uniformity is defined as the relative standard deviation (RSD) of airflow speeds measured at the specified section plane downstream of the unit's HEPA/ULPA face at a certain operating condition. A higher RSD value indicates less uniform of the measured parameters, while a lower RSD value corresponds to uniform pattern of the measured quantity. The standard deviation is calculated using the following formula:

$$\sigma = \sqrt{\sum_{i=1}^{N}(v_i - \bar{v})^2 \Big/ (N-1)}$$

The relative standard deviation (RSD), namely, the ratio of standard deviation (SD) to the average of the measured value, e.g., airflow velocity.

$$\text{Relative Standard Deviation (RSD)} = \frac{\sigma}{\bar{v}} x100\%$$

The unidirectional velocity profiles are measured on a plane, which is parallel to the face of HEPA/ULPA filter, with a distance of 15-cm (6-inch), 30-cm (1-foot), or 50-cm (20-inch) from the face of the HEPA/ULPA or its protective shield. For example, the users may perform velocity uniformity tests using a hotwire anemometer at an open section plane that is 15-cm (6-inch), 30-cm (1-foot), or 50-cm (20-inch) away from the face of HEPA/ULPA filters of the FFU.

Because cleanroom certification would involve operational testing in facilities, relevant literatures address airflow uniformity in controlled environments.[2][6][7][15][18] These literatures suggest or evaluate some aspects of uniformity testing and can be a starting point for readers to investigate the issue.

9.3 Interpretation of Results

Results from using this standard test method should not automatically be considered as being "certified." For example, an AMCA certified facility is not necessarily required for performance testing using this procedure.

9.4 Report Template

The following outlines the information recommended for reporting on standard laboratory test of FFU performance. It is used for summarizing and reporting performance information on an individual FFU.

9.4.1 Reporting Characteristics of the Unit Based on Manufacturer's Shipment

Manufacturer	Contact
Brand/Model	Serial Number
Unit Size	Fan Motor
Power Supply	Fan Wheel
Filter Efficiency	

9.4.2 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. 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 are recorded for a range of operable conditions of the unit. Normally, test conditions for 61-cm-by-122-cm (2-ft-by-4-ft) units are selected with the airflow rates no less than 300 ft^3/min (8.5 m^3/min) under the standard condition. The speed controller is initially set at its highest-speed setting followed by lower speed setting. Figure 3 shows operable conditions that were tested with various speed control setting.

9.4.3 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, total electric power demand can be calculated using the following equation, which is derived from laboratory testing results for the operating conditions as shown in Figure 1. The R-square of the polynomial 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 certainties in the power demand characterization based upon the laboratory testing.

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

where

- D_p is the pressure differential across the fan filter unit, in Pascal
- Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft^3/minute, scfm)

9.4.4 Total Pressure Efficiency

Total pressure efficiency 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.

$$\text{Total Pressure Efficiency } \eta_t = \frac{0.000471947443 Q \cdot D_p}{W_t}$$

Where

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

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

- W_t is the total electric power demand (EPD) of the fan filter unit, including all the electric power necessary to operate and control the fan filter unit, in Watt.

Additional graphs may be included to illustrate total electric power demand of the fan filter unit under selected operable conditions, e.g., $20 \text{ Pa} \leq D_p \leq 150 \text{ Pa}$, $Q \geq 9.9 \text{ m}^3/\text{min}$ (or $0.08 \text{ iwc} \leq Dp \leq 0.6 \text{ iwc}$, $Q \geq 350$ scfm).

Likewise, additional graphs may be included to illustrate total pressure efficiency of the fan filter unit under selected operable conditions, e.g., $20 \text{ Pa} \leq D_p \leq 150 \text{ Pa}$, $Q \geq 9.9 \text{ m}^3/\text{min}$ (or $0.08 \text{ iwc} \leq Dp \leq 0.6 \text{ iwc}$, $Q \geq 350$ scfm)

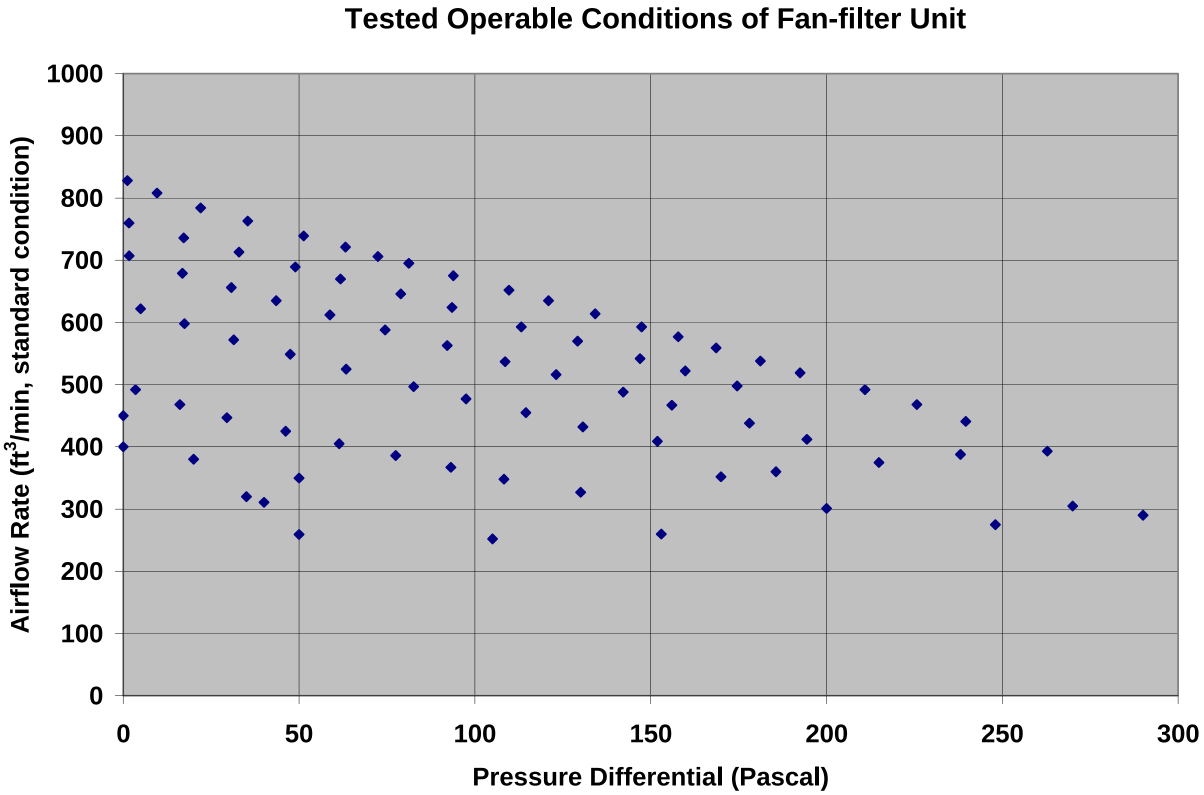

Figure 3 **Operable conditions with various speed-control setting**