

An Innovative Method for Dynamic Characterization of Fan Filter Unit Operation

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Tengfang Xu
Building Technologies Department
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
University of California, Berkeley, CA 94720-8134
One Cyclotron Road Tel: (510) 486-7810
BLDG 90R3111 Fax: (510) 486-4089
Corresponding author e-mail: ttxu@lbl.gov

Abstract

Fan filter units (FFU) are widely used to deliver re-circulated air while providing filtration control of particle concentration in controlled environments such as cleanrooms, minienvironments, and operating rooms in hospitals. The objective of this paper is to document an innovative method for characterizing operation and control of an individual fan filter unit within its operable conditions. Built upon the draft laboratory method previously published [1], this paper presents an updated method including a testing procedure to characterize dynamic operation of fan filter units, i.e., steady-state operation conditions determined by varied control schemes, airflow rates, and pressure differential across the units. The parameters for dynamic characterization include total electric power demand, total pressure efficiency, airflow rate, pressure differential across fan filter units, and airflow uniformity.

Keywords

Fan filter unit (FFU), cleanroom, energy efficiency, airflow uniformity, airflow rate, air pressure, test standard

1. Introduction

Fan filter units are widely used to deliver re-circulated air and provide filtration control for particle concentration in controlled environments such as cleanrooms, minienvironments, and operating rooms in hospitals. For example, much of the energy in cleanrooms (and minienvironments) is consumed by 2-foot x 4-foot (61-cm x 122-cm) or 4-foot x 4-foot (122-cm x 122-cm) fan filter units that are typically located in the ceiling of controlled environments.

Increasing energy costs in operating existing and future cleanrooms and mission-critical controlled environments have not only prompted end-users to seek and select higher-efficiency FFUs in their cleanroom applications, but also motivated a number of suppliers to understand their products and to develop more energy-efficient FFUs for future cleanrooms.

In recent years, the interest in understanding and improving fan filter performance has arisen among users, manufacturers, energy companies, professional organization, and research

institutes. For example, more and more manufacturers are interested in quantification of the energy performance of their fan filter units, and in a method for systematically characterizing fan filter performance that is affected by fan-wheel design, air-path and size, unit size, motor type, availability of airflow control and control schemes. Recent studies focused on assessment of energy performance of fan filter units based upon the laboratory testing with the units operating at a specific control setting, e.g., maximal fan-wheel speed setting.^{[2][3][4]} The studies provided useful methods and developed performance metrics that were useful. The available information from the studies was, however, insufficient to fully characterize a unit's operation within its achievable operating range under various control schemes. The new method presented in the paper benefits from a review of relevant industrial and international standards or recommended practices^{[5][6][7][10][8][9][11][12][13]}. This paper includes experimental steps that need to be taken in order to fully characterize energy and airflow performance of various fan filter units with different control techniques^{[14][15][16][17]}.

2. Purpose

The purpose of this paper is to present a new laboratory method including the test procedure developed for dynamic characterization of fan filter unit operation. This innovative method aims to quantify energy and airflow characteristics of individual fan filter units. The method has been validated and used to quantify the performance of individual 2-foot x 4-foot (61-cm x 122-cm) fan filter units, and to evaluate their functionality. The information developed from experiments using the method will be useful for suppliers and end users to understand, and more importantly, to characterize the dynamic operation of FFUs quantitatively under a variety of operating conditions.

3. Scope

This paper summarizes a new characterization method, including equipment requirements, and testing procedure, and focuses on fan filter units' energy performance and airflow uniformity. The method is limited to characterizing FFUs with filter media for removing particulates under normal cleanroom environmental conditions. The paper does not address noise or vibration issue, neither does it cover filters used for controlling airborne molecular contamination (AMC).

4. Laboratory Setup and Instrumentation

4.1 Setup

It is essential that the laboratory tests include accurate measurements of total electric power demand, airflow rates, and the static (and total) pressure differential across the FFU. A test rig is designed to allow variable and controllable airflow rates through the FFU in its operable range. The setup is expected to ensure no air leaks between the enclosed testing system and its ambient space.

Figure 1 and Figure 2 illustrate the experimental setup and layout for measuring airflow rate, static (and total) pressure, and total electric power demand. The unit's airflow rate, air pressure rise, total electric power demand were concurrently recorded for all operating conditions – defined and adjusted by varying the pressure differential and airflow rate across the FFU. As illustrated, airflow path may be designed as having restricted airflow coming to the FFU inlet (flow-through in Figure 1) or having open, non-restricted airflow coming to the FFU inlet (draw-

through in Figure 2) in the test rig. In the flow-through layout, airflow from immediate downstream of the FFU can be discharged to the atmosphere or a space with a specific static pressure.

Airflow rate measurement setup contains a single-nozzle duct (or multiple-nozzle bank when necessary) for recording airflow rates through the tested unit. Measuring the airflow rate using this setup is consistent with ISO Standard [10], and is expected to provide accurate and NIST-traceable airflow rate measurements.

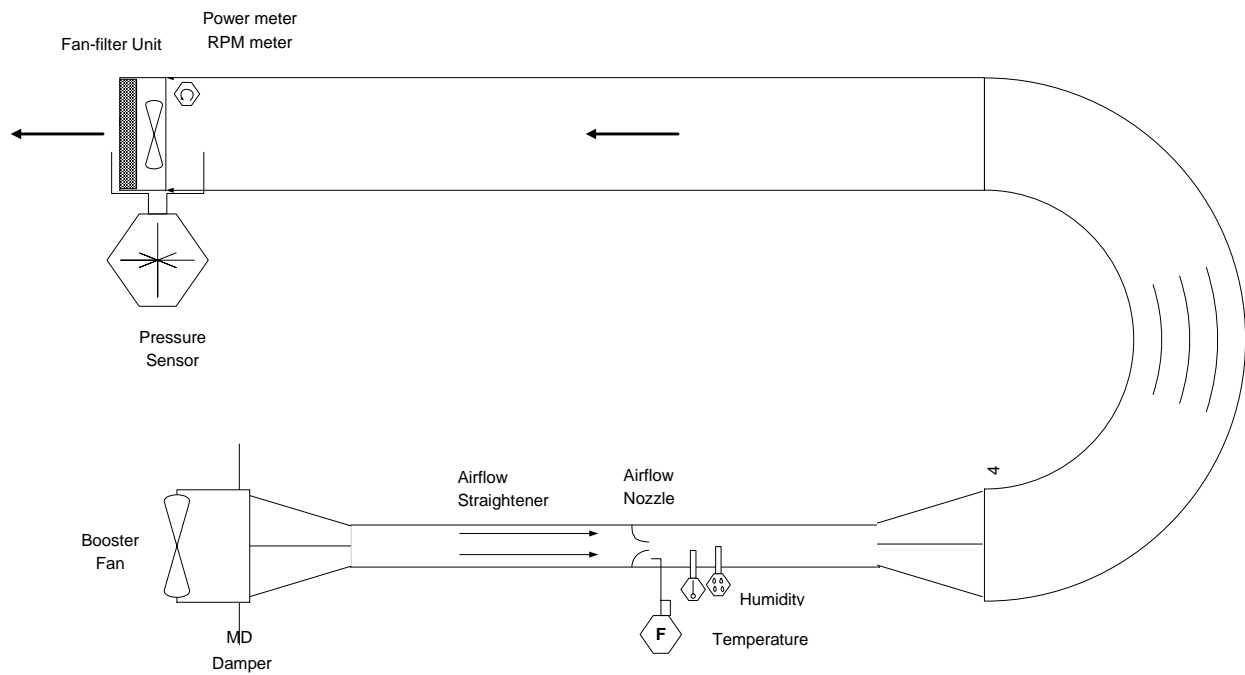


Figure 1 FFU Test Rig - Restricted Airflow at the FFU Inlet

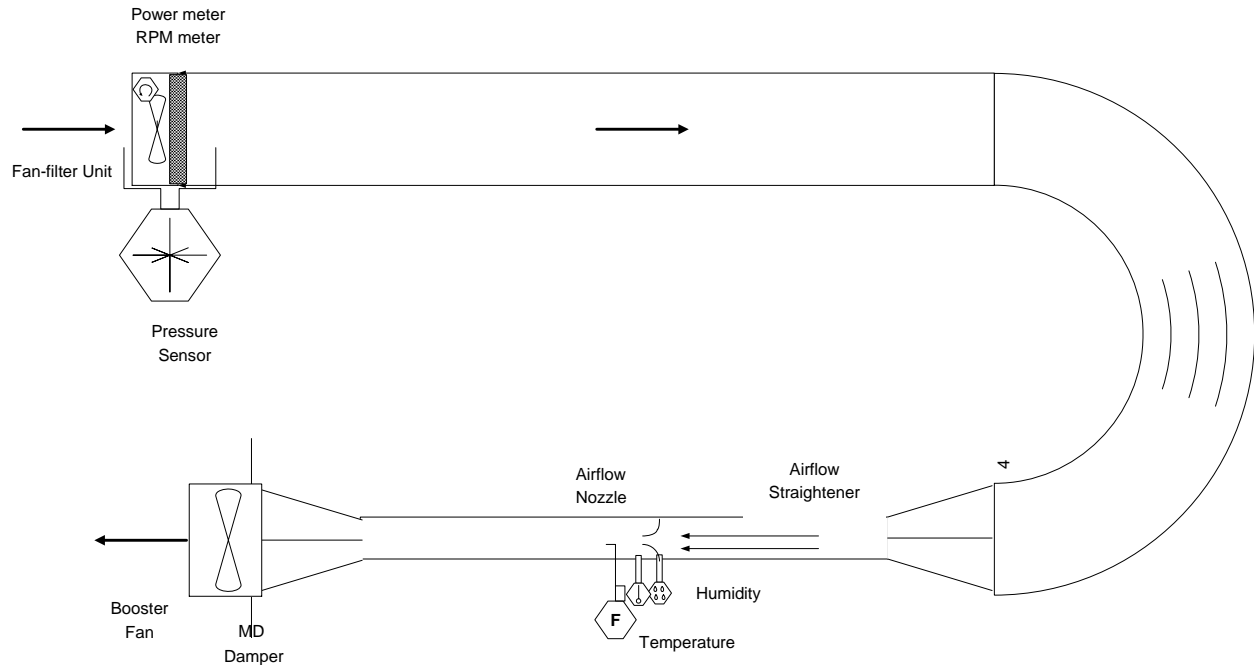


Figure 2 FFU Test Rig – Non-restricted Airflow at the FFU Inlet

Rigid ductwork or chamber that is fire-proof is required for the test rig. Maximum allowable air leakage should be controlled within 3% of airflow rates. When necessary, measures shall be taken to minimize the effect of leakage on actual airflow rates. Such measures may include the following: 1) sealing the leak; 2) correcting the airflow rates by subtracting the leakage from measured airflow rate.

The actual section size of ductwork mounted to the FFU was designed to be equal to or greater than the FFU cross-section size, i.e., frame of the ULPA filter. In the setup illustrated in Figure 1 where FFU discharges the airflow to an unrestricted space. 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. This conservatively met the minimal lengths suggested in AMCA/ASHRAE Standards used for testing performance of fans and other equipment^{[11][12]}.

Hydraulic diameter of a rectangular duct was calculated as

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

The diameter of the round ducts upstream and downstream of the flow nozzle was the same as that of the flow meter, which contained a flow straightener. Pending requirements for airflow uniformity in flow nozzle(s), the recommended minimum length of straight round duct upstream of the flow meter could be five times of the diameter of the flow nozzle, while minimum length of straight duct downstream of the flow meter was five times of the diameter of the flow nozzle. The actual lengths of straight round ducts connected to upstream and downstream of the flow

meter should be determined by the requirements supplied by the flow-nozzle manufacturers, and ISO Standards.^[10]

A minimum of one static pressure tap should be required and was installed at the center of section, which was 30-cm (1-foot) away from the upstream of the FFU inlet. Additional pressure taps may be placed inside the ductwork or chamber to record airflow pressures along the ductwork or chamber.

A non-contacting, optical RPM sensor was required to be installed at a fixed location upstream of the FFU inlet. The selected location shall allow the sensor to face the fan-wheel blades, and to directly monitor the rotating speeds of the fan-wheel blades. Normally, the fan-wheel blade had to be painted to enhance the contrast so that the RPM sensor could receive correct rotation signals. A prior test was performed to ensure the sensor was able to producing right signals from the rotating fan-wheel blades.

It is recommended that the measurements be conducted under iso-thermal and 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.

4.2 Instrumentation

The following enlists key instrumentation and required accuracies.

4.2.1 Airflow meter

The measurement of airflows through the FFU was conducted upstream (or downstream) of the FFU, with a measurement uncertainty to be within $\pm 5\%$.

The recommended range of the airflow rates to be measured depends on the actual 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][10][11][12]} The flow meter included a flow straightener and converging nozzle(s), with a Pitot-static type sensor centered at the outlet of the flow nozzle. Calibrations and validation were required and were carried out to ensure accuracies are satisfactory. Normally, additional flow nozzles or straighteners may be needed, pending requirements for the selected airflow nozzle(s) and actual airflow rates. For example, for 61-cm by 122-cm (2x4') fan filter units in this experiment, we adopted Brandt Model NZP1031-10"-1-CF flow meters, which may measure airflow rates from 250 to 1300 cfm (7 to $37 \text{ m}^3 \text{ min}^{-1}$), 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-cm x 122-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

Various pressure transducers should be used to measure or monitor airflow rates and air pressures in various locations in the test rig. Pressure transducer(s) with sufficient accuracies shall be used with the airflow meter to measure and record airflow rates through the flow nozzle(s). 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 being tested. The types of pressure transducers may include Pitot Tubes sensors.

The output signals of pressure transducers should be logged with 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 $\pm 1\%$ of reading. The calibration of the multi-channel pressure transducer system should 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 are expected to 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 of air pressures along the ductwork or chamber. The pressure taps may consist of Pitot tubes to be installed along the center of sections of the ductwork leading to the fan filter unit. The Pitot tubes are used to quantify the air pressures at specific locations within the test rig.

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.

4.2.4 Barometer

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

4.2.5 Electric power meter

Total electric power demand shall include the fan, frequency drive motor, speed control device, transformer when applicable, etc. Total electric power demand shall be measured using accurate electric power meters. The measurement and recording shall be performed concurrently with

airflow rate and pressure measurements. Pending power supply requirements (e.g., AC vs. DC power, one-phase vs. three-phase AC power), appropriate power meters shall be used to measure true power demand of the unit. The measurement output of true mean electric power demand for the whole unit included 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 should 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 shall be 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 is required, along with necessary accessories such as reflective tape or color coating. The RPM meter should be regularly calibrated and include NIST Traceable Certificate of Calibration, 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, electric power demand, and fan-wheel speed 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, power, and current from transducers or sensors. The output signals of data loggers, such as airflow and pressure differential, air temperature and humidity may be recorded with a computer-based data acquisition system.

5. Operation and Control of Fan Filter Unit

In order to control the airflow rate and pressure differential across the FFU tested and characterize the FFU within its operation range, an ancillary fan and a damper should be needed to modulate static (and total) pressures and airflow rates across the FFU. The ancillary fan is used to booster the test rig's capability to emulate various external resistance. Such a booster fan should normally include variable-speed controller in order to adjust the airflow rates through the fan.

Adjustment of airflow rates under a certain fan-wheel speed setting can be achieved by one of two means: 1) varying fan-speeds of the booster fan thereby changing airflow rates, and 2) 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-speeds of the booster fan and controlling the pressure drop across the damper is employed to adjust actual airflow rates through the unit.

When applicable, the FFU shall be tested for each fixed level of the fan-wheel's rotational speed setting that is preset by the speed controller. Adjusting damper positions and booster-fan's speeds modulates the pressure differential and airflow rate across the FFU. The corresponding pressure differential, unit airflow rate (and airflow speed), and total electric power demand shall be recorded for operating conditions selected under each preset level of the fan-wheel's rotational speed setting. For an FFU equipped with speed modulation device using a VSD motor, the fan motor in FFU shall be set at various speed-setting within the 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 level of speed-setting for the fan-wheel's rotational speeds, e.g., 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% of its maximal speed-setting.

6. Laboratory Characterization Method

The unit airflow rate, fan-wheel rotational speed, pressure differential across the FFU, and total electric power demand shall be recorded concurrently at any given operating condition. In order to generate various testing conditions, the pressure differential across FFU shall be controlled at various levels for each fan-wheel speed setting when applicable. For example, within each incremental 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 power demand and performance metrics can then be obtained for a specific operating condition and/or a specific range of operating conditions, e.g., pressure differential of 0.5-inch water (125 Pa) coupled with an actual airflow rate of 520 cfm (245 Ls⁻¹) that a unit is capable of supplying.

6.1 Unit airflow rate

Actual unit airflow rates (and/or airflow speeds) correspond to the operating condition affected by fan-wheel speed control and pressure differential across the FFU. The airflow shall be measured at a steady-state and is flowing through a circular conduit by means of pressure differential devices (orifice plates, nozzles and/or Venturi tubes) that are inserted into circular

6.2 Fan-wheel rotational speed

To test FFU at various and 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 recorded concurrently with other parameters.

6.3 Pressure differential across the FFU

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

6.4 Power supply and total electric power demand

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.

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.

6.5 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 its 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) [11].

6.6 Minimizing 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)^[15].

The air leakage can be quantified and minimized 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. Measures to reduce leakage of test rig should be carried out to ensure leakage ratio is at a minimal level for representative operating conditions.

7. Laboratory Test 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. The procedure has been validated through characterizing a variety of 2-foot x 4-foot (61-cm x 122-cm) fan filter units made in Asia, Europe, and North America.^{[14][15][16]}

- 1) Perform calibration of measurement equipment and ensure all devices are working properly.
- 2) Perform air leakage test of test rig system, with the open-end of the ductwork sealed. 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.
- 3) Install an RPM meter to monitor the fan-wheel speeds of the FFU in the test rig.
- 4) Install pressure taps in and around FFU when necessary.
- 5) Connect wiring for all instrumentation and data acquisition system, which include pressures, flow meter, power meter, RPM meters, temperature, humidity, etc.
- 6) 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.
- 7) Record ambient-air conditions, including temperature, humidity, atmospheric pressure.

- 8) Install a guiding tool such as a rod through a transparent window so that the speed setting of FFU's fan-wheel could be externally adjusted. This step especially useful for flow-through (Figure 1) test rig where the FFU inlet and the speed dial is inside the ductwork.
- 9) Turn on FFU and then turn on data acquisition system to show the trend of air temperature, pressure, airflow rate, and power demand versus time.
- 10) Synchronize the time stamps for all data loggers and data acquisition. Save the data files.
- 11) Before taking measurements, wait for the airflow and operation of test equipment to stabilize. The parameters to check for stabilization include airflow rate, pressure, temperature, fan-wheel speed.
 - a) Normally continuous operation with a minimum of 30-minute should be required.
 - b) Longer waiting time may be necessary if the preset airflow rate, air pressure or temperature is considerably in a non-steady-state.
- 12) Adjust and measure airflow rates and pressure differentials through the unit.
 - a) Set the unit's speed-control setting at its maximal position.
 - b) 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).
 - c) 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.
 - d) 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.
 - e) Each recorded operating condition should be stabilized and maintained for at least three to five minutes. Record all parameters for each operating condition. Normally a minimum of ten operating conditions should be recorded.
- 13) 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.
- 14) 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.
- 15) Save the data files. Take additional notes when necessary.
- 16) Record ambient-air conditions, including temperature, humidity, atmospheric pressure.
- 17) Convert and/or export the experimental data files to appropriate formats for calculations and analysis.

18) 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.

8. Metrics for Characterization and Experimental Validations

The purpose of conducting laboratory testing is to characterize dynamic operation for an FFU under various operable conditions, and to provide reporting on energy performance for the FFU with HEPA/ULPA filters in a consistent way. In addition to reporting relevant characteristics of an FFU, such as filtration efficiency and filter size, the following includes key performance metrics and sample results from experimental validation^{[14] [15] [16]}.

8.1 Airflow rate and pressure differential

A combination of independent magnitudes in airflow rate and pressure differential defines the actual operating condition of a fan filter unit. The operating conditions changed with the changes in airflow rates and the pressure differential across the unit. Several other factors affects the combination of achievable combination of airflow rate and pressure differential – the design and control schemes of fan filter unit, and the actual fan-wheel rotation speeds, and power supply to the unit. Figure 3 shows the operable conditions of one FFU sample measured at four different fan-wheel speed setting. At each speed setting, airflow rates through the FFU decrease with the increase in pressure differential across the unit. The maximum airflow rate that this unit can provide would be close to 600 cfm (283 L/s) at which the pressure differential would be almost zero Pascal. In addition, the maximum pressure rise across the unit would be 140 Pa with a minimal airflow rate of approximately 300 cfm (142 L/s).

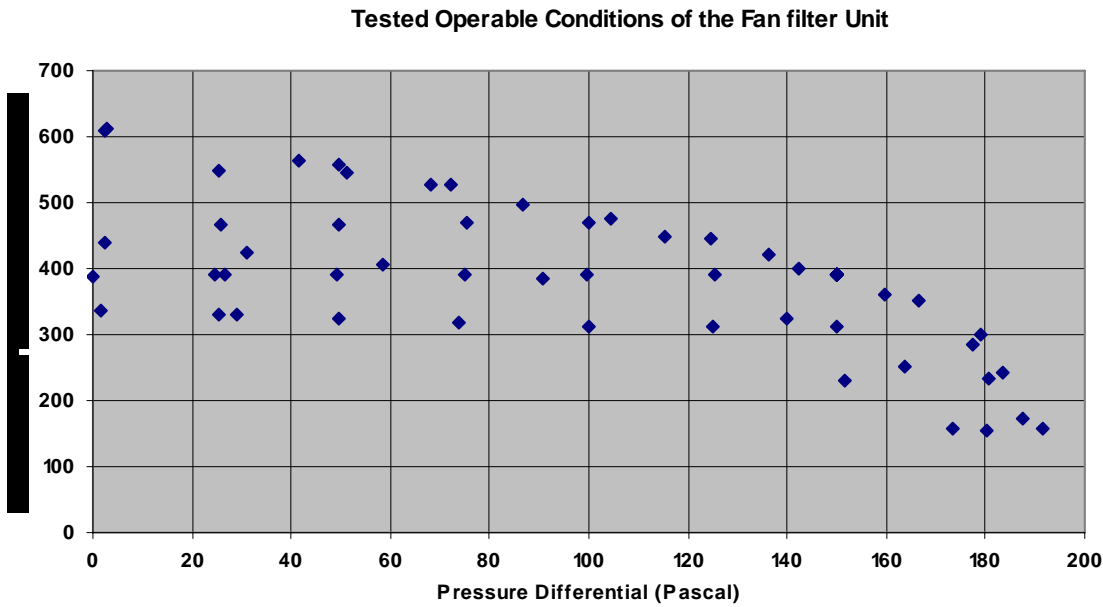


Figure 3 Operable conditions with various speed control setting

8.2 Total electric power demand

Total electric power demand include the total power supplied to a fan filter unit, including electric power for fan motor, controller, and accessories such as transformer when applicable. Total electric power demand can be measured and characterized for any operable condition - airflow rate (or actual airflow speed) with the actual pressure gain across the unit, based upon laboratory test data under the full operating range of an individual unit. Based upon the laboratory data, total electric power demand may be quantified as a function of airflow rate and pressure differential across the unit.

8.3 Total pressure efficiency

Total pressure efficiency (η) is used as a yardstick for quantifying energy efficiency levels, which is defined as the ratio of actual pressure power to total electric power demand (EPD) for a fan filter unit. Total pressure efficiency can be measured and characterized for any operable condition based upon laboratory test data, as it relates to operating conditions that are defined by unit airflow rates and pressure differential.

$$\eta = 0.0471947443 \frac{D_p Q}{EPD}, \%$$

where

Q

is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft³/minute)

D_p

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

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

8.4 Energy performance index

Energy performance index (EPI) is similarly used as a yardstick for quantifying energy efficiency levels for a given pressure differential across individual FFUs. It is defined as the ratio of total electric power demand per airflow rate across a fan filter unit. EPI may be characterized for any defined operating condition, as it is a function of unit airflow rates and pressure differential.

$$EPI = \frac{EPD}{Q}, W / cfm$$

where EPD is the total electric power demand (EPD) of the fan filter unit including all the electric power necessary to operate the fan filter unit, in Watt
 Q is the airflow rate across the unit under standard atmospheric condition, in scfm (standard ft³/minute)

8.5 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. Because cleanroom certification would involve operational testing in facilities, relevant literatures address airflow uniformity in controlled environments, [5]^{[8][9][13][17]} however, none of the open literature address laboratory testing of individual fan filter units. This paper present a method specifically defining and quantifying the values of airflow uniformity for an individual fan filter unit.

Airflow uniformity to characterize a fan filter unit is defined as the relative standard deviation (RSD) of airflow speeds measured at a specified section plane downstream of the unit's HEPA/ULPA face. A higher RSD value indicates less uniform of the measured parameters, while a lower RSD value corresponds to more uniform pattern of the measured quantity. The value of airflow uniformity may change depending on the actual operating condition defined by airflow rate and pressure gain, and the distance away from the HEPA/ULPA face. First, the standard deviation, σ , is calculated using the following formula:

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

Where

- v_i is the unidirectional velocity measured on a plane 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. Each V_i should be measured within a grid with a spanning distance of no more than one quarter of the filter size. For example for a 61-cm x 122-cm (2-ft x 4-ft) FFU, the grid size should be no more than 15-cm x 30-cm (6-inch x 12-inch).
- \bar{v} is the average of measured velocity v_i
- N is the number of measurement points on an open plane where the velocity anemometer is located.

Then, the relative standard deviation (RSD) - the ratio of standard deviation (SD) to the average of the normal velocities at the same measured plane, is calculated as

$$RSD = \frac{\sigma}{\bar{v}}$$

The RSD can be quantified for a measurement plane that is 15-cm (6-inch), 30-cm (12-inch), or 50-cm (20-inch) away from the face of HEPA/ULPA filters of the FFU.

9. Summary of Conclusions, and Recommendations

The characterization method and the metrics developed can be used to characterize functionality and dynamic energy performance of individual FFUs under applicable operation and control schemes. Based upon the experimental validations, the new method provides a solid base and tool for dynamically characterize the operation of individual fan filter units equipped with various control schemes. ^{[14][15][16][17]} Using the laboratory characterization method and procedure presented in this paper, experimental characterization for 61-cm-by-122-cm (2-ft-by-4-ft) fan filter units with various design, operation, and control was feasible. Additionally, the paper presents methods for characterizing airflow uniformity in addition to energy performance of FFUs, and defines the airflow uniformity specifically applicable to individual fan filter units.

Areas of recommendations include further investigations to improve cost-effectiveness and easiness of the test rig by studying effects of the sizes of the test rig and unit (i.e., sizes of ductwork, length of straightener to flow sensor), ambient air conditions (e.g., air temperature), airflow directions on the measured performance of individual units. In addition, the effects of the test rig and fan filter unit on airflow uniformity will need to be investigated.

10. Acknowledgement

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Bio

Tengfang (Tim) Xu, PE, obtained his Ph.D. from UC-Berkeley. He is with Lawrence Berkeley National Laboratory, managing and performing R&D projects to quantify energy efficiency and improve performance of commercial, residential, and industrial buildings, including cleanrooms, data centers, and healthcare buildings. Dr. Xu was the Contamination Control Technical Vice President of IEST (2005-2007), and a recipient of numerous national awards for scientific papers, publications, and professional services. At Berkeley Lab, he is involved in the development of innovative methods and protocols that are instrumental in formulating standards to characterize fan filter units. In addition, he manages and performs evaluations of energy, airflow and filtration requirements for cleanrooms and minienvironments. Xu's interests include the production and dissemination of new knowledge and techniques to improve environmental and energy

performance of mission-critical buildings. Dr. Xu is a Technical Editor for the *Journal of the IEST*, and serves on the editorial board of *Building and Environment*, Elsevier Scientific. Email: TTXU@LBL.Gov; <http://eetd.lbl.gov/Staff/XuTT/>.