Using Field Measurements of Air Filter Performance and HVAC Fan Energy Measurements to Select Air Filters with Lowest Life Cycle Cost

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ABSTRACT

Properly selected and maintained, building air filters provide a simple and often overlooked opportunity for significant reductions in electric energy use. These savings can be achieved while maintaining or enhancing indoor air quality (IAQ) by filtration of incoming and recirculated air in building HVAC systems. This article reviews the technologies behind air filtration in buildings and describes methods to select air filters and to measure electric energy use from fans and blowers, as well as the field performance of particulate air filters.

Using the criteria described, air filters and energy use are evaluated in several common settings, including offices and mixed-use buildings, manufacturing plants, laboratories, and hospitals. Several case studies are briefly described, showing in-situ filtration performance, electrical energy measurements, life cycle cost calculations, and total cost of ownership for air filters of various designs and qualities.

Air filter performance is characterized using the test procedure outlined in ASHRAE Standard 52.2-2007 App. J, which includes a discharge step that neutralizes the temporary static charge present on some types of filter media. This step is important because the temporary static charge can result in inflated air filter minimum efficiency reporting value (MERV) ratings that are higher than those exhibited by affected filters when deployed in air handlers shortly after installation in an AHU.

Air filter guidelines and ventilation for acceptable indoor air quality in occupied buildings is discussed in ASHRAE Standard 62.1-

2007. In-situ air filter performance is measured using the detailed procedures outlined in ASHRAE Guideline 26-2008. These procedures include field measurements of ambient air and downstream particle concentrations, airflow across the filter bank, and resistance to airflow from clean and loaded air filters.

Cost of ownership factors include the air filter purchase price, operating cost (fan energy), installation labor, and disposal. Electrical energy measurements are made using a power datalogger and other equipment used to evaluate motors and drives. Fan energy and airflow interactions with other system components are discussed, including constant and variable air volume system designs and variable frequency drives.

INTRODUCTION

Energy costs and polluted outdoor air are two reasons to consider air filtration, rather than increased outdoor air ventilation, to achieve more comfortable indoor air. Owners and operators of commercial and institutional buildings can benefit from methods that provide clean, filtered air to occupants while minimizing the cost of providing this filtered air. In most buildings and climates, the majority of the cost of providing filtered air is the electricity consumption of the fans in the HVAC system.

When ventilating an occupied building, the goal is to provide the building owners and occupants with clean indoor air as cost effectively as possible. Properly selected and maintained, building air filters provide a simple and often overlooked opportunity for significant reductions in electricity cost, maintenance labor, and solid waste disposal. These savings can be achieved while maintaining or enhancing indoor air quality (IAQ) by filtration of incoming and recirculated air in building HVAC systems. This article reviews the technologies behind air filtration in buildings and describes methods to select air filters and to measure electric energy use from fans and blowers, as well as the field performance of particulate air filters.

The use of long-life, lowest life cycle cost air filters in a facility achieves two goals, both attractive to building owners and managers:

1) Energy efficient air filters contribute to corporate initiatives to reduce carbon footprint and solid waste.

2) Reduced fan electric consumption provides an immediate and ongoing impact to the "bottom line".

In a manufacturing and production setting, a further cost/benefit analysis shows the relative ease with which this reduced electrical energy consumption is achieved when compared to the investment required to increase "top line" revenue.[1]

Using the criteria described, air filters are evaluated in several common settings, including offices and mixed-use buildings, manufacturing plants, laboratories, and hospitals. Several case studies are described, showing in-situ filtration performance, electrical energy measurements, life cycle cost calculations, and total cost of ownership for air filters of various designs and qualities.

AIR FILTER TECHNOLOGY

The technology of particulate air filtration is fairly well established. A good summary on air filtration is found in Chapter 8 of Burroughs and Hansen[2]. Most commercial building filters are disposable, made by pleating porous fibrous materials into pleat packs, then mechanically fastening them into rigid frames or cartridges. Electrostatic and electronic designs are also available. Air flows through particulate filters, typically at a design face velocity of 350-500 fpm, and airborne particulates become trapped in the fibrous structure. The air exiting the filter is cleaned of some fraction (determined by filter design) of the ambient particulate load and is then delivered to the breathing space in the building.

Airborne particulate and gas-phase odors consist of a variety of materials, including soil, rock, ash, soot, pollens, and dust, as well as man-made emissions from fires, combustion (power plants), and vehicular traffic (tires, rubber). Also included are bioaerosols (airborne bacteria, fungi, virus, molds, etc.), often in water droplets from cooling coils, water leaks, condensation, or sneezing occupants. Gas-phase odors may come from both outdoor and indoor sources.

Fibrous filter designs vary, depending on the application and the initial purchase price, and include rigid mattes and panels, bag or pocket filters, and pleated panels (1″ to 6″ deep), as well as deeper cartridges (typically 12″ deep).

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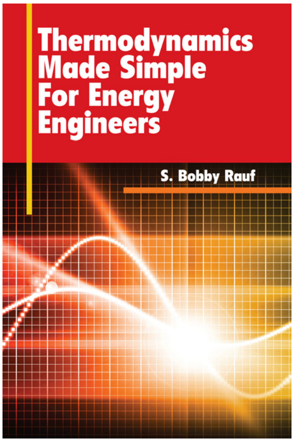

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The purpose of this book is to provide an overview of important principles and concepts in the field of thermodynamics, written in a fashion that makes this abstract and complex subject easy to comprehend. Intended to serve the needs and interests of energy-involved engineers, the content, concepts and principles are presented in a way which also will allow many non-engineering professionals with some math background to follow the material and gain useful knowledge. For energy engineers who may have been away from direct engineering practice for a period of time, this book can serve as a quick and effective refresher. Thermodynamic topics including enthalpy, entropy, latent and sensible heat, heats of fusion, and heat of sublimation are clearly presented. Also covered are phases of substances, the law of conservation of energy, SFEE, the first and second laws of thermodynamics, ideal gas law, and respective mathematical statements. The author provides an examination of specific thermodynamic processes, as well as heat and power cycles such Rankine, Carnot and the differences between them. Case studies illustrate various thermodynamics principles, and each chapter concludes with a list of questions or problems for self-assessment, with answers provided at the end of the book.

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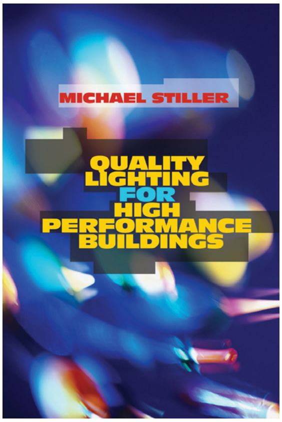

In the U.S., buildings account for 40% of primary energy use, 72% of electricity consumption, and 39% of CO_2 emissions. Indoor lighting accounts for a large portion of our energy use, and we sorely need better, more efficient systems to illuminate our large structures as well as our homes. But as we seek greater efficiency and meet new green construction codes, it is imperative that we avoid sacrificing lighting design that enhances our productivity, comfort, and health. This is an overview of the basic concepts of quality, indoor lighting, visual comfort and interest, and integrated design as they relate to the practice of lighting design. Energy efficient lighting technologies, including LED lighting and digital control systems, and design strategies that increase visual comfort and productivity are discussed in plain language, to give all readers, whether architects, interior designers, engineers, building trades professionals, or students, a broad understanding of the art and science of energy efficient quality lighting.

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Figure 1 shows several pleated panels of varying thickness.

Figures 2 and 3 depict two modern filter cartridge designs. Some *vee-cell filters* (Figure 2) are notable for the large amount of media they deploy, resulting in long service life at low pressure drop and very low total cost of ownership. *Pocket filters* (Figure 3) have historically been more popular in Europe than in North America. Recently, advanced

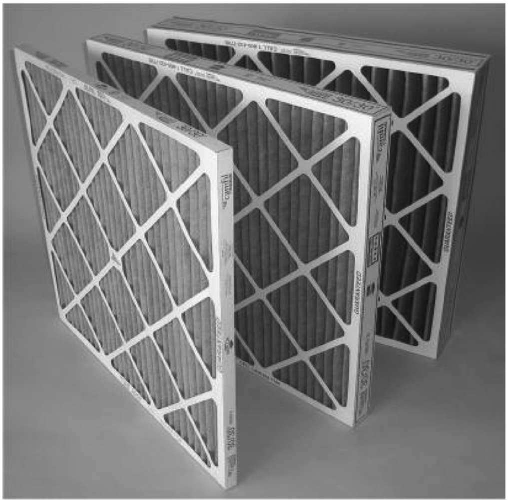

Figure 1. 1″, 2″, and 4″ pleated filter panels

Figure 2. Vee-cell air filter

Figure 3. Pocket or "bag" filter

designs have been introduced which do not require a panel prefilter and offer some of the lowest life cycle costs of any filter design on the market.

AIR FILTER PERFORMANCE

In order to select the most cost effective air filter for use in a given HVAC system and building space, the user must first establish a desired minimum filtration efficiency level or particulate load for the space. In North America, the most commonly used method for characterizing air filter performance is the test procedure outlined in ASHRAE Standard 52.2[3]. The 2007 version of the standard contains significant improvements over earlier versions, including the test method enhancements described in Appendix J. This enhancement includes a discharge step that neutralizes the temporary static charge present on some types of synthetic (polymeric) filter media. The results are reported as *MERV-A*. This discharge step is important because temporary static charge on a filter can result in inflated air filter MERV ratings (compared to the standard test method), often several steps higher than those exhibited by affected filters shortly after installation in an AHU[4].

Some savvy building users write their air filter specifications to explicitly require MERV-A test results, thereby avoiding the purchase of air filters that deteriorate in performance shortly after installation.

ASHRAE 62.1, INDOOR AIR QUALITY AND FIELD MEASUREMENTS OF AIR FILTER PERFORMANCE

Air filter guidelines and ventilation for acceptable indoor air quality (IAQ) in occupied buildings is discussed in ASHRAE Standard 62.1-2007[5]. Two methods are described; one is prescriptive, the ventilation rate procedure (VRP), and one is performance-based, the indoor air quality (IAQ) procedure. The VRP is more commonly used. Users can label the use for given spaces inside a building and design the prescribed amount of ventilation in cfm or cfm per person for that space.

The U.S. Building Council's (USGBC) voluntary Leadership in Environmental Design (LEED) rating system provides an opportunity to earn an *indoor environmental quality credit* by designing the building ventilation system to improve indoor air quality for occupant comfort, well-being, and productivity. This improvement is accomplished by "increasing breathing zone outdoor air ventilation rates by at least 30% above the minimum rates required by ASHRAE Standard 62.1-2007..."[6], which cites the use of VRP rates. However, the weaknesses of equating increased ventilation with improved indoor air quality are well known, as discussed at length by authors in various places, including Hansen[7]. Two of the larger problems with this assumption are: (1) In many locations, outside air is frequently of poorer quality than filtered inside air; (2) Outdoor air must be tempered in order to make it comfortable. Along with controlling air temperature to the benefit of the building occupants, relative humidity must be controlled as well, and dehumidification in wet climates is expensive.

By contrast, the indoor air quality procedure (IAQP) is rarely applied and is commonly perceived as too subjective, although it has been successfully applied with impressive energy savings in some high-profile situations. (Grimsrud[8] describes ten years of monitoring in a chain of big-box retail stores.) However, the IAQP suffers from weaknesses, including a lack of consensus for which *contaminants of concern* are appropriate and sufficient to treat during design, as well as the inability to ensure compliance with unknown, future changes in building use.

In the summer of 2010, a task force of ASHRAE members was established to provide guidance for using the IAQP[9]. The committee's scope is to "develop specific application direction to allow users to apply the IAQP method…in commercial applications, educational facilities, (and)…all spaces defined within the main body of the standard."

With additional application guidance, the IAQP may well take its place as an essential design tool for optimizing the balance between outside air ventilation, air filtration and recirculation, and HVAC energy costs. Some IAQ practitioners consider the IAQP the best available method for achieving clean breathing air inside sustainable and net-zero energy buildings.

A field test method for making in-situ air filter performance measurements is outlined in ASHRAE Guideline 26-2008 for field testing of general ventilation filtration devices[10]. These procedures include field measurements of ambient (inlet) air and downstream particle concentrations, airflow across the filter bank, and resistance to airflow (pressure drop) from clean and loaded air filters. Some air filter manufacturers and independent laboratories offer this service of in-field testing of particle filter installations[11]. Briefly, comparison filter banks are installed under a carefully subscribed set of operating conditions. Airflow is monitored using a portable instrument and probe. Particle counts upstream and downstream of the filter banks are made with an isokinetic sampling probe and an optical particle counter. Numerous controls and cross-checks are built into the test procedure to ensure reliability. Results are calculated as fractional particle removal efficiencies for each range counted by the particle counter, and they may be used to measure MERV ratings in the field.

AIR HANDLER UNITS (AHUs) AND ENERGY MEASUREMENT

The distribution energy associated with fan and pumping subsystems in an HVAC system can often amount to 40-50% of a building's electrical energy use[12]. Even modest reductions in fan energy use from variable fan speed controls and lower pressure drop air filters (at the MERV level desired for the building use and occupant comfort) can result in significant operating savings to the building's energy budget.

Relatively few studies appear to have been published on the relationship of HVAC electrical energy consumption and air filters. Professor Jeff Siegel at the University of Texas in Austin and his colleagues have published several informative papers on this subject[13,14,15]. Some of this research was sponsored by ASHRAE.

Fan power consumption is determined by the quantity of air moved by the fan; hours of operation; electrical voltage; current and power factor drawn by the fan motor; amount of pressure required to be produced by the fan to overcome losses through the ductwork and components (i.e. coils and air filters); and efficiencies of the fan, motor, and drive.

Assume a system efficiency of 0.65 = fan efficiency = 0.70 x motor efficiency = 0.93 x drive efficiency = 0.98. In a variable frequency drive (VFD)-controlled system, the energy used by the AHU is approximately:

$$\text{kWh} = \text{hours} \times 0.746 \times \text{measured airflow [cfm]} \times \Delta p \text{ [in. w.g.]} / (6356 \times 0.65)$$

Constant speed systems controlled by in-duct static pressure sensors will generally respond to lower pressure drop filters with increased airflow, since the fan speed cannot automatically change. Thus, rather than energy savings, more air changes are produced. In contrast, variable air volume systems controlled with in-duct static pressure sensors, especially those incorporating variable frequency drives, are able to reduce fan motor speed when lower pressure drop filters are installed. Systems of this general description have become more common in the past few decades.

LIFE CYCLE COST AND AIR FILTERS

Thornburg described a method of analyzing the long-term costs associated with comparative air filter purchase decisions in a building. The method is useful for selecting the most cost effective system over the lifetime of a building's HVAC system. He states:

> Life Cycle Cost (LCC) analysis is an excellent tool for determining the most cost effective filtration solution to meet user needs. LCC

> is a method of analyzing the long-term costs of a buying decision. "Long-term" does not refer to the life of the filter, but the life of the building, 20 years in a typical LCC analysis. The objective is to choose the most cost effective system over this 20-year span—which may be very different from the lowest up-front cost that the purchasing agent sees on the quote. The initial cost of a filter may only represent about 4% of the total LCC. Thus, buying a filter based on price alone would be like buying a car based solely on the cost of the tires![16]

Cost of ownership factors include the air filter purchase price, operating cost (fan energy), installation and removal labor, and cleaning and filter disposal. Figure 4 shows the typical contribution of the components to life cycle cost. The components include the purchase price, installation/removal labor, waste disposal, fan energy, and any associated duct and coil cleaning costs.

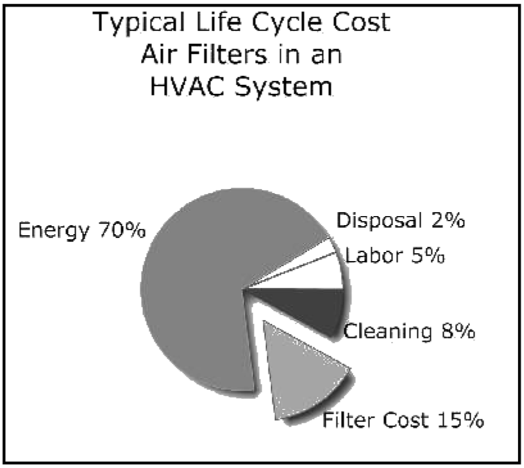

Figure 4. LCC components of filter ownership

Thornburg cautions the end user to first establish the desired minimum filtration efficiency level based on building objectives (i.e., IAQ control/comfort, compliance, LEED criteria, equipment or process cleanliness, etc.) Once the desired efficiency level is established by the user, life cycle costs may be minimized for that given level of efficiency. To accomplish this goal, there are a few nuances of air filter behavior that must be understood:

- Calculation or measurement of a filter's true average resistance to airflow over its lifetime
- Importance of comparing filters of equal efficiency (as measured in the field)
- Need to determine true (discharged) filter efficiency (MERV vs. MERV-A)

There are some subtleties to filter selection that are not commonly understood. The first is that real life efficiencies and test report efficiencies of air filters are often not the same, especially when comparing small diameter glass fiber media to large diameter synthetic fiber, "charged" media. Second, real life resistance to airflow rises over time (loading curve) but is rarely linear, so simple averaging of beginning and ending pressure drops gives inaccurate results. Loading curves vary with filter design, media type, and construction. Thornburg goes on to assert that, typically, a real life, or true efficiency MERV 13 (80-85% dust spot) air filter is the minimally effective filtration solution. A filter delivering this level of performance will capture the majority of small particles entering the filter and will eliminate the need for duct cleaning over the 20-year life span. MERV-13 is also the minimum filter efficiency required by the LEED process in order to earn credit for indoor air quality[17].

The vast majority of life cycle cost calculations show that buying air filters on initial price alone results in a higher total cost of ownership, as the initial investment accounts for only a small fraction of the total life cycle cost. The available evidence is conclusive—selection of air filters based on the initial price is almost always a false economy[18,19].

MEASUREMENT OF AHU PERFORMANCE

A variety of suitable instruments are available to measure airflow and air pressure in AHUs. Static pressure drop across air filter stages may be measured with a simple Magnehelic (Dwyer Corporation) or similar differential pressure gauge. The author used Magnahelic gauges and a Shortridge Model 870C meter for recording airflow and pressure drop.

There are situations where building operators have electric energy monitoring in place in an AHU. With some preparation and analysis, they can readily document the energy savings associated with different choices of air filters in their AHUs. Some operators have programmed their building automation systems to log this data for some or all AHUs in their buildings.

Without direct measurements of electricity consumption, estimates may be made by monitoring airflow and pressure drop in the AHU, then calculating electricity consumption using common equations such as those referenced above. Direct comparisons of filter banks containing different models of filters can be made by temporarily setting airflow to constant levels, allowing the fan motor to ramp up or down as different pressure drop filters are deployed. Another way to do this is to log the watts consumed by an AHU motor over time as the system ramps up and down in response to internal and external loads and control programs.

For spot measurements, relatively simple and common equipment can be employed to measure electricity use in AHUs. The easiest and most convenient method, when available, is to take fan motor wattage readings from the VFD display. When this method is not available, a sophisticated, non-contact (“clamp-on”) power meter may be employed to monitor fan motor wattage over time at the output of the VFD.

Field measurements of fan motor electric power can be conducted quickly for snapshot estimates, but dataloggers must be employed to collect data over longer periods to understand electric use over the months and years it takes for a final filter to load and require replacement.

A planned follow-up to this article will present case studies where field measurements of fan electric consumption have been made to compare competitive air filter installations. The goal of these field measurements is to make a direct estimate of the electric energy savings available when using the most efficient filters available with the same MERV-A (discharged) ratings. In some cases, these measurements are daylong snapshots, while in other cases long-term, logged, electric energy consumption is analyzed. These measurements are primarily used to confirm the estimates made by life cycle cost calculations.

CASE STUDIES

The following case studies will be discussed in detail with the publication of a follow-up article:

- A 7200-cfm rooftop AHU at a hospital in South Central USA
- Dual 34,000-cfm AHUs serving one floor of a three-story office building in South Central USA
- Four 50,000-cfm AHUs serving a common plenum in a four-story office /corporate laboratory building in the Mid-Atlantic states
- Two identical 34,000-cfm AHUs serving a two-story office/ university research laboratory building in the Mid-Atlantic states
- Four 30,000-cfm AHUs serving a five-story university classroom building in Southeastern USA
- Three identical 32,000-cfm AHUs serving a common plenum in a manufacturing space in Mid-Western USA.
- Dual 35,000-cfm AHUs serving one floor of a mid-rise office building in New England

The above listed case studies, as well as additional ones and field demonstrations, are in the process of being documented for later publication. Additional publications discussing energy use and air filtration in buildings are also planned. Please contact the author for additional documentation.

CONCLUSIONS

The case studies show significant differences in field performance and life cycle costs for different air filters with similar MERV ratings. The lowest total cost of ownership is almost always achieved with filters that do not have the lowest initial (purchase) cost. Energy is saved when systems operating near capacity are slowed, using a combination of variable speed fan control and lower pressure drop filters. These savings are predicted by life cycle calculations made by using electric energy equations, and they are confirmed with spot and long-term measurements of fan energy.

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