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ORIGINAL ARTICLE

Characteristics, Pressure Drop, and Capture Efficiency of New and Repeatedly Washed Heavily Loaded HEPA Filters

KEN SMIGIELSKI[1], FARHANG AKBAR-KHANZADEH[2], FARIDEH GOLBABAEI[3*]

[1] *First Solar, Inc., Perrysburg, Ohio;*
[2] *University of Toledo, Ohio;*
[3] *Department of Occupational Health, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran*

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ABSTRACT

An extensive literature review revealed few published reports on the wet cleaning and reusing industrial HEPA filters, except for those on metallic and glass fiber filters. Accordingly, the effects of particulate loading on pressure drop and the capture efficiency of new custom-fabricated high-efficiency particulate air (HEPA) filters were determined in this research and the findings were compared with those of the same filters after being wet cleaned and reused multiple times. A set of five samples from three different types of HEPA rated filtration media, made of polypropylene (Puritrate®), Teflon and glass fiber filters, were fabricated in the cylindrical shape. Each filter was mounted in a specially designed filter-testing unit and gradually loaded with airborne particles of cadmium telluride (CdTe) in 10-gram increments up to a total of 100 grams. During the loading, the face velocity of each filter was kept constant at 17. 8 m/s (3500 ft/min). Four filters (two Puritrate® and two Teflon) were fully loaded 4-10 times. Each time, they were wet cleaned in dilute (< 4%) nitric acid-soaked for 24 hours, rinsed with deionized water, and gradually dried at ambient temperature under a laboratory hood until the filter gained its original weight. The glass fiber was used as a reference medium; it was loaded and tested only once and was not wet-cleaned or reused. The pressure drop across all filters (new or reused) increased by cubic model expression as the filters were gradually loaded. Baseline pressure drop on the new (unused) filters ranged from 45 Pa (Puritrate®) to 115 Pa (Teflon). As the filter loading progressed, the pressure drop ranged from 146 Pa (Puritrate®) to 306 Pa (Teflon). After each wet-cleaning and drying cycle, the filters' pressure drop returned almost to their original baselines. All filters, new or reused, performed well, with particulate capture efficiencies exceeding 99.97% at 0.3 µm. The results suggested that certain custom fabricated HEPA filters can effectively be wet-cleaned and reused.

KEYWORDS: *Recycling HEPA filters, Filter pressure drop, Filter loading characteristics*

INTRODUCTION

According to the Lawrence Berkeley National Laboratory [1], no published valid estimate exists on the benefits of enhanced particle filtration for buildings in the United States. However, the laboratory cites a report that socially speaking, the annual benefits of air filtration due to reduced illness and premature death could range up to $144 per office worker and up to $30 per industrial worker. Mechanical air purification by filters, as a major component of most of the ventilation systems, is essential in a majority of manufacturing operations and buildings. In addition to improving the breathing air quality, mechanical filters can protect machinery and products from harmful particles. Depending on the level of air contaminant control, filters may often need to be replaced, resulting in significantly higher disposal costs. Due to the rising operational and waste generation costs, health concerns can be alleviated by a reduced number of filter replacements. For example, although the high-efficiency particulate filter (HEPA) may be required in many industrial situations, it may not be used because of its high initial and maintenance costs. Air-purifying filters can generally be sorted into washable and non-washable classes: washable filters are usually made of thick fibers that can

Corresponding author: Farideh Golbabaei
Email: F.Golbabaei@Yahoo.Com

become wet without getting structurally damaged; while, non-washable filters are built of thin, paper-like materials, which become damaged easily if wet washed [2]. HEPA filters are defined as air-purifying media capable of capturing at least 99.97% of 0.3 µm particles. Filter efficiency is defined based on particle capture capability, not the ability to be washed or reused. Some venders claim that the new models of HEPA filters are washable, but these types of HEPA filters have no standardization and thus, the claims are not substantiated. Additionally, no third party exists to certify expertly that these "washable" models function properly after being washed. Most of the commercial size HEPA filters are very fragile [3], and the key question remains whether these filters could be wet-cleaned and reused.

An extensive literature review revealed few published reports on the wet-cleaning and reusing of industrial HEPA filters, except for those on metallic and glass fiber filters [4]. Thus, this study was initiated with the main objectives of (a) identify qualified HEPA filter material capable of maintaining integrity (e.g., a good mechanical structure with at least 99.97% capture efficiency of 0.3 µm airborne particles) after being wet-cleaned; (b) Fabricate cartridge filters with the materials identified; (c) Design a test process in which the filter is loaded with industrial airborne particulate contamination, while keeping the face velocity of the filter constant and monitoring the pressure drop across the filter; (d) Wet-clean each fully loaded filter in an acidic solution and distilled water and then, dry the filter to its original weight; (e) Determine the particle capture efficiency, airflow, and air pressure drop across the new filter and the reused filter.

MATERIALS AND METHODS

Testing HEPA Filter

The filters were fabricated and examined using a custom-designed Filter-testing Unit (Fig.1). The unit included a filter-holding compartment (box), a cylindrical filter, an end cap, a suction fan, instruments to measure airflow (rate and velocity), an analytical scale to weigh the filters (clean and loaded), and a fume hood to dry the wet-cleaned filters. In this study, the selection of air filters was based on the experience of different types of air filters. In the preliminary phase, a series of flat (not pleated) sheet filters were evaluated in terms of (a) particulate capture efficiency by a particle counter (LASAIR® Model 310C, Particle Measuring Systems based in Boulder, Colorado, USA) and the ambient air contaminant as the particle challenge; (b pressure drop across the filter by differential pressure gauge (Shortridge Instruments, Scottsdale, Arizona, USA), and (c) structural strength by observing structural integrity. In the next phase, three filter media were selected to examine their performance while being loaded with cadmium telluride (CdTe) particles, and washed/cleaned in dilute acid solution and rinsed with distilled water as follows: (a) Several small sheets of Puritrate® filters (Polypropylene media made by Write Material Research, Dayton, Ohio, USA), each approximately 30 x 30 cm (12 x 12 inch), were made using a unique operation of spray coating and evaluated for particulate capture efficiency and pressure drop.

The Puritrate® medium was selected because, despite its structural similarity to the glass fiber filter, it would not be damaged by dilute acid, (b) The Teflon media was a coated film sheet encapsulated between two backing materials. While it was washable in dilute acidic solution, it had reasonable particulate capture efficiency and pressure drop. The Teflon filter was selected because its use is common in air filtration; and, (c) The glass fiber filter was selected due to its good particulate capture efficiency and low-ppressure drop. However, the glass fiber filter can be damaged in the dilute acid solution.

At the final phase of this study, the completed versions of cylindrical shaped HEPA filters by Puritrate®, Teflon, and glass fiber were fabricated and tested. The surface area of the filters ranged from 1.47 m^2 (15.8 ft^2) to 2.02 m^2 (21.7 ft^2) as shown in Table 1. All filters were pleated with the same tool using custom-made end caps and a canister with a length of 29.2 cm (11.5 inch). To monitor the velocity of the airstream at the cross-section of the exhaust duct (clean side), a pitot tube was used while connected to an AirData Multimeter (Shortridge Instruments Inc., Scottsdale Arizona, USA).

Particulate Capture Efficiency of Filters

The particulate capture efficiency of each new filter was determined prior to filter loading. The particulate capture efficiency (*Eff*) of each filter was defined as:

$$Eff = 100\ (1- L) = 100\ (1- d/u)$$

Where; L is penetration ratio or leak; d and u are respectively the downstream and upstream concentrations of particles. Ambient particles of 0.3 µm were used as the upstream and downstream contamination, measured by a particle counter (LASAIR 310C®, Particle Measurement Systems Boulder, Colorado, USA). A sealed flange was custom fabricated using a LASCO 4” (10 cm) Flange Fitting D-3139 with a LASCO ½” (1.25 cm) diameter and 90-degree adaptor (LASCO Fittings Inc. Brownsville, Tennessee, USA). The filter was sealed into the flange and the LASAIR 310C particle counter was connected to the flange adaptor, allowing air to be pulled through the filter while recording the number of particles penetrating the filter.

Particulate Contaminant Used in Filter Loading

Particles of CdTe were used as air contaminant for filter loading. The particles were generated from a laser ablation process used in a manufacturing line and recovered from a two-stage dust collector. The size analysis of the airborne particle by the particle counter (LASAIR 310C®, Particle Measurement Systems Boulder, Colorado, USA) showed that approximately 95% of the particles had a size of ≤ 0.3 μm, 4.8% between 0.3 and 0.5 μm, and 0.2% ≥ 0.5 μm. In this experiment, particles of CdTe was used due to (1) their size characteristics; and, (2) A green energy semiconductor company, which uses CdTe as the primary chemical for the production of solar panels, was interested in the project and provided facilities for this research.

Filter Loading Process and Cleaning (Recycling)

To clean a fully loaded filter, it was placed in a plastic container of dilute nitric acid (<4% concentration) and soaked for 24 hours. The filter was then rinsed with deionized water and placed on a scale under a laboratory hood to gradually dry in ambient air until reaching its original (unloaded) weight. The Filter-testing Unit (Fig. 1) was assembled with a filter housing designed to secure the test filter for the loading process. A vacuum system, "shop vacuum" with HEPA filter (RIDGID Blower Vacuum Module WD 1680, Emerson RIDGE, Elyria, Ohio USA), re-wired with a rheostat for adjusting the air velocity. The vacuum system was positioned at the air discharge side of the filter housing and drew air through the filter, creating a negative air pressure within the filter housing. Two multi-meters (AirData Multimeter, Shortridge Instruments Inc., Scottsdale, Arizona USA) were used; one to monitor the pressure drop across the filter, and the second to determine the airflow velocity. The closed container of CdTe particles was placed on an analytical scale and the particles were made airborne and introduced to the filter housing and filter. Each filter was loaded in increments of 10 g of air contaminant up to 100 g, and with each loading session, the pressure drop across the filter was determined. The particles, settled on the interior walls of the filter housing, was estimated to be less than 0.1% of the total particles introduced to the filter housing. The air velocity was kept constant at 17.8 m/s (3,500 ft/min); this air velocity was chosen because it is common in manufacturing processes. During the loading sessions, 11 pressure drop readings were documented, each corresponding to one of the 11 filter loading scenarios (0, 10, …, 90, 100 g).

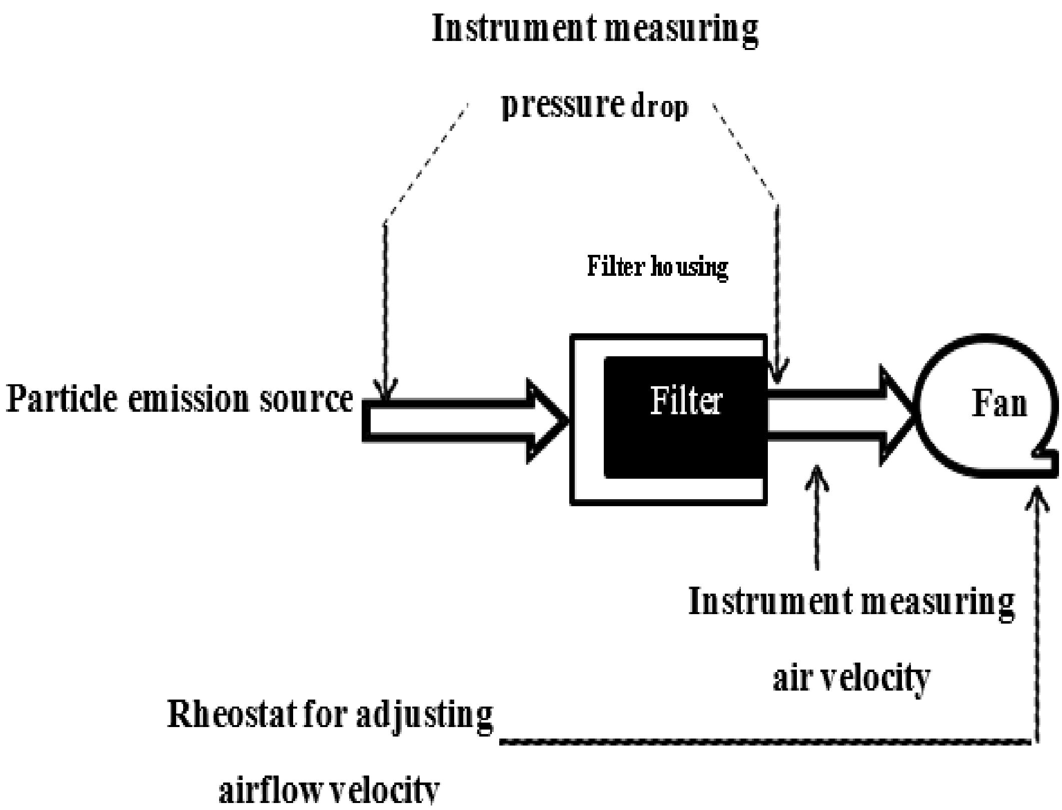

Fig.1. Filter-testing Unit with its major components

RESULT

Particulate Loading Characteristics of Filters

Table 1 describes the five studied filters either as new filters or after being loaded with particles, wet-cleaned, and dried. Baseline pressure drop of the new (unused) filters ranged from 45 Pa (0.18-inch WG) for Puritrate® to 115 Pa (0.46 inch WG) for Teflon. As the filter loading continued, the pressure drop approached 146 (0.45-inch WG) for Puritrate® and 306 Pa (1.2-inch WG) for Teflon. The pressure drop across all filters remained below 500 Pa (2.0 inch WG), a limit suggested by many filter venders [5] at which the HEPA filters should be replaced. After each cycle of wet cleaning and drying, the pressure drop of the filters returned to the original baseline levels.

All filters, new or reused, showed a particulate capture efficiency of at least 99.97%. The pressure drop across the cake (Δpc) of each tested filter was depicted versus its normalized particulate loading (g/m^2). It created 27 filter-loading sessions.

To examine the characteristics of the filters during the loading and wet cleaning processes, the new and reused Puritrate® and Teflon filters were loaded with the contaminant, wet cleaned, and reused multiple times. The glass fiber filter was loaded only as a new filter; it was not suitable for being wet cleaned. All filters were appraised for their overall physical condition, surface area, percent particulate capture efficiency, and pressure drop before, during, and after each loading. Tests on the filters were cut when the recorded performance fell below 99.97 at 0.3 µm. A close visual observation confirmed that the filter media started disintegrating after repeated wet cleaning and reusing.

Major findings of this study are: (a) Both Puritrate® and Teflon filters tolerated the wet cleaning and drying processes while maintaining their structural integrity and a minimum particulate capture efficiency of 99.97% at 0.3 µm; (b) The first and second Puritrate® filters were wet cleaned (and reused) three and five times, respectively. The relationship between pressure drop and loading of the new and reused (after three times wet cleaning) filters are depicted in Fig. 2. The two Puritrate® filters showed similar loading characteristics; for the same loading capacity, the reused filters built up less pressure drop than the new filters; (c) The first and second Teflon filters were wet cleaned (and reused) five and nine times, respectively. Fig. 3 provides a comparison on the relationship between pressure drop and loading in new filters and those wet-cleaned for three and five times. The two Teflon filters showed similar loading characteristics for the same loading levels, the reused filters built up less pressure prop than the new filters; and, (c) The pressure drop and filter loading have the same pattern in new glass fiber, Puritrate®, and Teflon filters (Fig. 4). The best model explaining the effects of particle mass loading (w) on the pressure drop (Δp_c) over the filter cake is presented in Table 2.

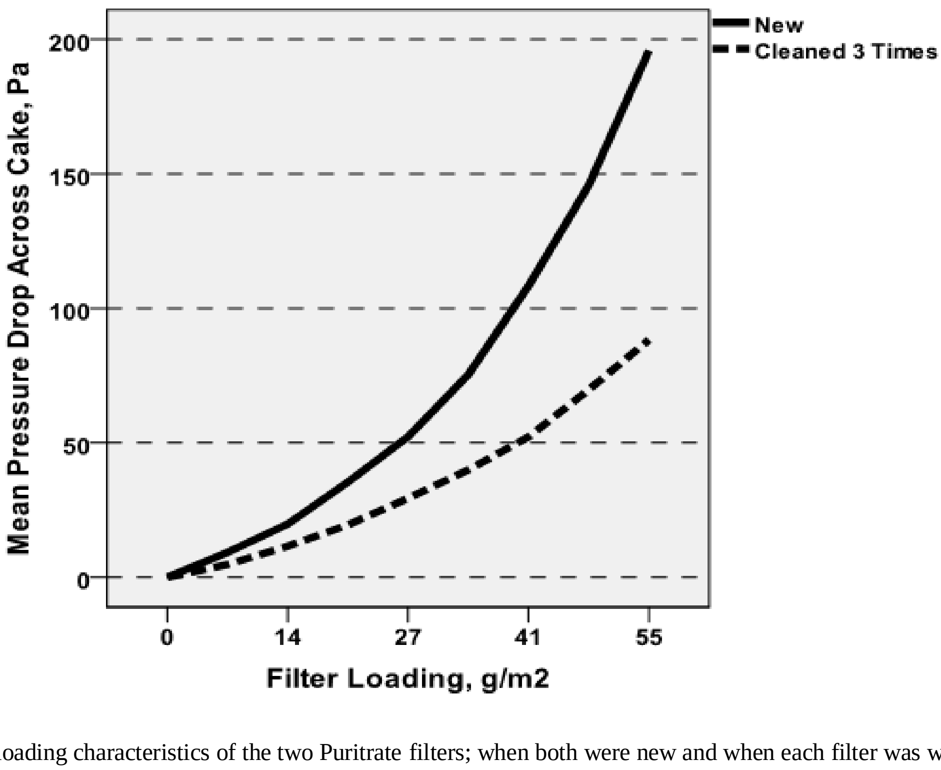

Fig.2. Average loading characteristics of the two Puritrate filters; when both were new and when each filter was wet cleaned and reused three times

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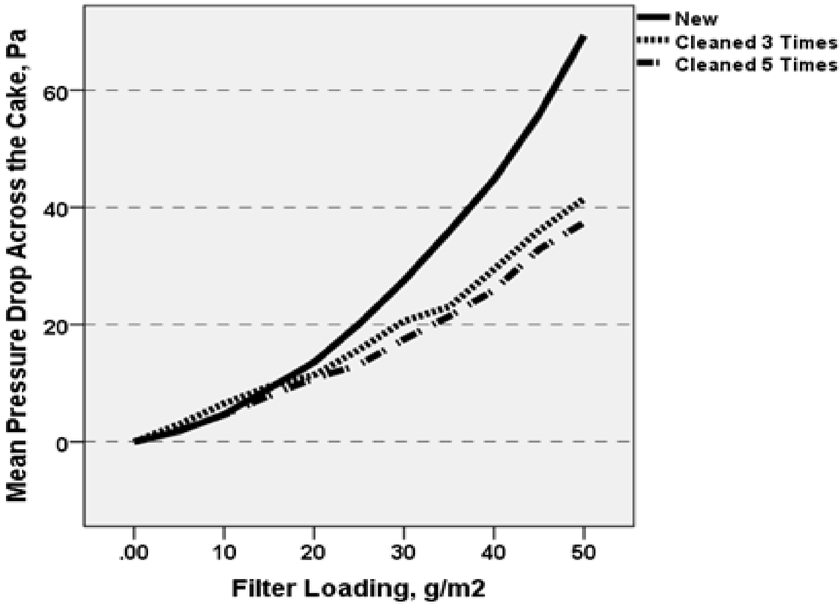

Fig.3. Average loading characteristics of the two Teflon filters; when both were new and when each filter was wet cleaned and reused three and five times, respectively

Table 1. Description of the five filters studied

Filter Media	Filter Surface Area, m^2 (ft^2)	Filter Initial Pressure Drop (Pa)	
		New (Unused)	Reused (Min-Max)
Puritrate 1	1.47 (15.8)	59.4	45.2 – 49.8
Puritrate 2	1.45 (15.6)	58.3	54.2 – 59.3
Teflon 1	2.02 (21.7)	112.0	103.0 – 121.0
Teflon 2	2.02 (21.7)	117.0	102.0 -115.0
Glass Fiber	1.72 (18.5)	73.9	-

Face velocity for the filter was 17.8 m/s (3,500 ft/min); capture efficiency was at least 99.97% at 0.3 µm.

Table 2. Factors in the "cubic," expression: $\Delta p_c = a + b_1 w + b_2 w^2 + b_3 w^3$; w = particle loading mass, Δp = pressure drop

Filter Type	**n**	**a**	**b_1 (x 10^{-3})**	**b_2 (x 10^{-3})**	**b_3 (x 10^{-3})**
Puritrate	10	- 0.4	+ 994	– 0.221	+ 0.374
Teflon	16	- 0.2	+ 62.5	– 2.610	+ 0.156
Glass Fiber	1	- 0.2	+ 1414	– 11.200	+ 0.602
Total	27	- 0.2	+ 791	– 1.900	+ 0.253

DISCUSSION

Implications, Strengths and Weaknesses

The findings of this study implied that a certain type of HEPA filters could effectively be wet cleaned and reused. The reused filters performed efficiently and with considerably less pressure drop compared to the same new filters. The properties of the recycled filters can encourage reuse of HEPA filters, which reduces maintenance costs as well as the cost of solid waste collection and disposal.

The main shortcoming of wet cleaning and drying of used filters could be the need for additional equipment and tools that may be unavailable or its high cost of operation. Another concern might be that wet-cleaning filters may help grow harmful levels of biohazards (e.g., bacteria, mold and mildew) on these filters. Due to the use of acidic solution (4% nitric acid) in this experiment, there was a little chance for the survival of any living material in the filters. An additional concern could be the generation of harmful liquid waste from washing the filters. Our preliminary cost estimate shows that any additional costs are relatively low; for example, the very weak acidic solution is not expensive. In addition, managing the liquid wastes (similar to the present test), can be cost-effective and practical with a few simple designs.

Comparison with Other Methods of Recycling

The used filters are occasionally recycled to recover filter material. [6] Accordingly, there are very few published reports on the significant changes of industrial HEPA filters after cleaning and reusing water. Several manufacturers of commercial small portable air cleaning units (designed for office and home use) as well as some vacuum cleaners refer to cleaning and reusing HEPA filters by rinsing them with water or vacuuming [2]. However, very little detail is available on how effective these processes can be in removing the contaminants from the filter, control of the contaminants after removal, or verification of the wet cleaned filter for the reuse.

There are recycling methods other than wet cleaning and reusing of industrial air filters. For example, one attractive and seemingly practical option is the use of the common "clean-in-place filter, which is performed by applying the "back-pulsing" mechanism. However, three concerns arise with using this method: (1) cost of the system for creating the back-pulsing, (2) safe management of the airborne and collected contaminants, and (3) problems with the aggressive air movement, which may create contaminated-air leaks within the filter housing. The "back-pulsing" also creates fluctuations in the emission of air contaminants, ambient temperature, and humidity.

There are also other types of cleanable filters, composed of metallic, ceramic, or glass fibers. In 1996, Bergman et al. [4] suggested that cleanable steel HEPA filters should be made by the steel fibers of preferably less than 0.5 µm to meet the standard requirements of the HEPA filter in the production units. They concluded that, in general, the metallic and ceramic powder filters show a pressure drop of more than 6,230 Pa (25-inch WG), so they cannot be suitable candidates for the use and reuse as the HEPA filters are. The ceramic fiber has too large pores diameter to meet the HEPA efficiency requirement. Bergman et al. [6] suggested that the glass fiber filters were a promising material to make cleanable HEPA filters. However, these filters are not suitable to be wet cleaned. In our study, a glass fiber filter was loaded and tested and its loading characteristic (Fig. 4) was similar to those of Puritrate® and Teflon; however, it was not wet cleanable.

Another reusable filter is the "electrostatic filter," which is usually framed in aluminum. Several layers of woven polyurethane and polypropylene fibers make this filter statically charged when air is passed by. These charges attract and retain small particles with an efficiency of up to 93% [7]. Venders recommend that the easiest way to clean an electrostatic filter is to use a vacuum cleaner hose for sucking the particles directly from the filter. However, if the filter is too dirty, they recommend flushing clean it with water using a rubber hose [7]. Ji et al. [8] conducted a study entitled "effect of particle loading on the collection performance of an electret cabin air filter for submicron aerosols". Electret filters are composed of permanently charged electret fibers and are widely used in cases where high collecting efficiency and low-pressure drop are required. These filters are expensive and may costly to maintain.

Pressure Drop vs. Filter Loading

The analytical expressions by Endo et al. [9], Endo and Alonso [10], and Herman et al. [11] have been modified and used by others [12-13] to explain the effects of particle loading on the collection performance of air filters. However, under the conditions of this study, the best model explaining the "effects of particle loading (w) on the pressure drop (Δp_c) of the cake" was cubic: $\Delta p_c = a + b_1 w + b_2 w^2 + b_3 w^3$.

The relationships showed high values at the coefficient of determination: $r^2 \geq 0.997$. Table 2 summarizes the factors associated with different types of filters. Kim et al. [13], by discussing filter loading, found a linear relationship ($\Delta p_c = a + b w$) between pressure drop and filter loading. It should be noted that the contaminant (soot agglomerates) in their study was in the "mg" range, while in our study the contaminant was in the "g" range.

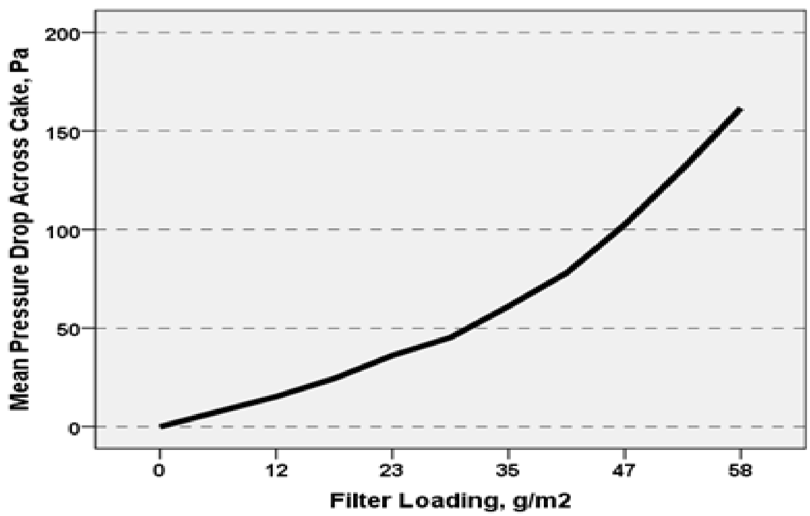

Fig.4. Filter loading characteristics of the glass fiber

CONCLUSION

The findings of this study indicated that:

- Puritrate® and Teflon filters allowed for wet cleaning, drying, and being reused multiple times while maintaining acceptable capture efficiency at levels exceeding 99.97%.
- Wet cleaned (recycled) filters showed a similar but lower cumulative pressure drop than the new filters.
- Puritrate®, Teflon, and glass fiber filters showed similar loading characteristics. For the same loading levels, reused filters built-up less pressure drop than the new filters.

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