

FIBER ENTANGLEMENT EFFECTS ON FILTRATION EFFICIENCY AND AGING OF FILTER MEDIA FOR PARTICULATE CONTROL IN THE STEEL INDUSTRY

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ABSTRACT

The control of particulate matter emissions in the steel industry is essential for compliance with environmental regulations and for reducing associated health risks. This study investigates the efficiency and durability of meta-aramid filter bags, comparing needle-felt and hydroentanglement media in both virgin condition and after laboratory aging. The objective is to diagnose operational failures and assess the energy demand of the filtration process. The methodology included the physicochemical characterization of particulate matter generated during the desulfurization process, as along with e structural analysis of the filter media (basis weight, thickness, efficiency and air permeability). Samples were collected along the length of the filter bags in order to evaluate fiber heterogeneity. Filtration performance was assessed according to VDI 3926, covering the stages of initial operation, artificial aging, stabilization, and aged operation, with continuous monitoring of pressure drop and collection efficiency. Preliminary scanning electron microscopy (SEM) results showed that desulfurization particulate matter consists of agglomerates with predominantly spherical morphology and a chemical composition mainly composed of Ca (~59%) and Fe (~22%). The needle-felt material exhibited a higher average basis weight (~613 g/m²) and thickness (~2.34 mm) compared to the hydroentangled medium (~559 g/m² and ~2.11 mm, respectively). Filtration tests using desulfurization dust indicated that both media maintained collection efficiencies above 99.9% in both the initial and post- aging conditions, demonstrating high particle retention capability. Therefore, this study aims to provide technical support for the selection of the most suitable filter media, contributing to improved energy efficiency and extended service life in industrial filtration systems.

KEYWORDS:

Bag Filter, Environmental Control, Filter media, Industrial Process Filtration, Needle Felt, Hydroentanglement, VDI 3926.

INTRODUCTION

Industrial processes are recognized as major sources of atmospheric pollutants, especially fine particulate matter (PM), including particles with aerodynamic diameters smaller than 2.5 μm (PM_{2.5}) and 10 μm (PM₁₀) (Bhatti et al., 2021; WHO, 2023, 2021; WHO Regional Office for Europe, 2026). Human exposure to these particles has been consistently associated with an increased incidence of cardiovascular and respiratory diseases, including stroke, as well as the development of chronic conditions and potential adverse effects on multiple organ systems (Ramon et al., 2023; Schraufnagel et al., 2019; Singh et al., 2023; Thangavel et al., 2022; Wei et al., 2019).

In the steel industry, the control of particulate matter emissions is essential for regulatory compliance and the protection of human health. Bag filters are employed due to their high efficiency and resistance (Cirqueira et al., 2019; Park et al., 2019; Zhou et al., 2023). However, their performance depending on the appropriate selection of filter media properties such as mechanical resistance, durability, permeability, and cost (Donovan, 1985; El Messiry et al., 2024; Matteson and Orr, 1987; Sutherland, 2008). The internal structure of the filter medium is directly influenced by the fiber entanglement method. In this study, two manufacturing approaches are considered: needle-felt, in which fibers are mechanically interlocked using barbed needles, and hydroentanglement, where high-pressure water jets promote fiber bonding and consolidation, resulting in distinct structural characteristics. (Fukasawa et al., 2021; Hutten, 2016; Karthik et al., 2016; Russell, 2022; Sutherland, 2008).

Previous studies have highlighted the importance of filter structure on performance. Liu et al. (2019) analyzed conventional polyester filters and filters coated with polytetrafluoroethylene (PTFE) membranes, demonstrating that pore size significantly affects both filtration resistance and efficiency, particularly for fine particles such as PM_{2.5}. Similarly, Singh et al. (2023) reported that filter media with different surface treatments exhibit distinct particle retention behaviors, with membrane-coated needle-punched materials showing lower emissions, reduced residual pressure drop, and lower dust penetration. Hydrophobic-treated media also demonstrated superior performance compared to conventional filters. Under high dust loading conditions, the influence of the filter medium was found to be more significant than that of the particulate material. In addition, Vieira et al., (2026) evaluated the effects of industrial aging on meta-aramid filter media and reported substantial changes in structural, morphological, and filtration properties including reductions in permeability and mechanical integrity.

In this context, the present study aims to investigate and compare the filtration efficiency and pressure drop of meta-aramid filter bags manufactured by needle-felt and hydroentanglement techniques, under both virgin and laboratory-aged conditions. To this end, the particulate material and filter media were characterized, and filtration tests were conducted using an experimental setup in accordance with the VDI 3926, employing a pulse-jet cleaning system.

MATERIALS AND METHODS

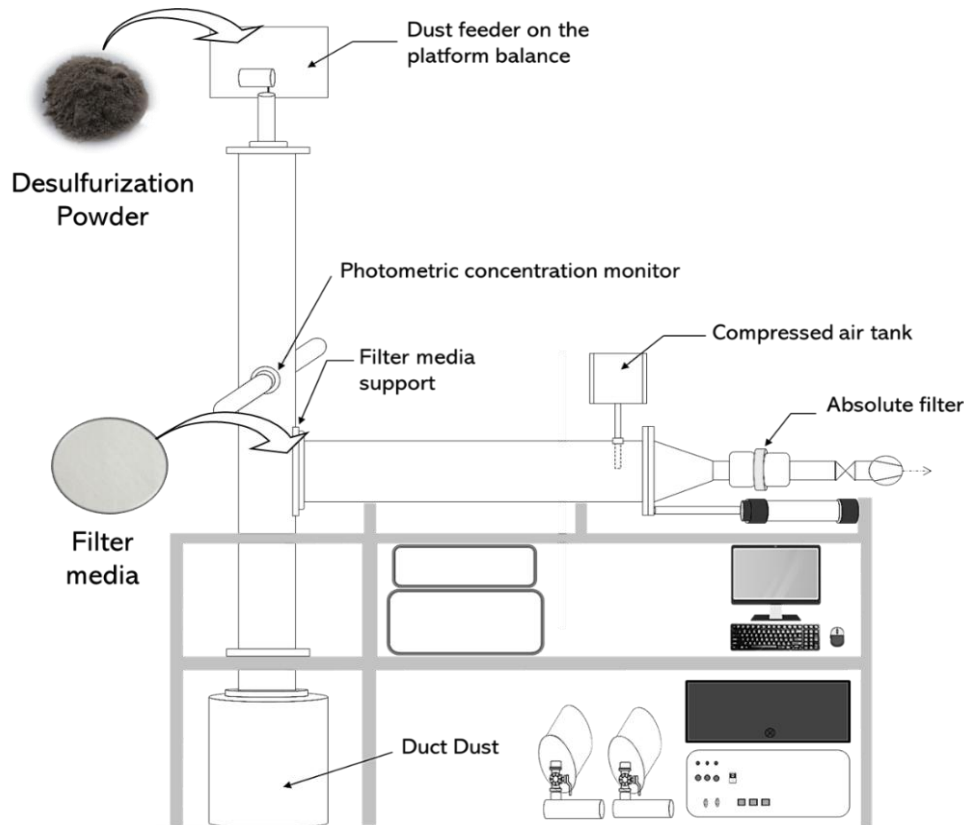
The particulate matter was provided by a steel industry and collected from the pig iron desulfurization process.

Prior to characterization and filtration tests, the particulate material was sequentially sieved (24 and 32 mesh) and dried at 70 °C for at least 24 h to remove moisture. Particle density was determined by helium pycnometry using an *AccuPyc 1330 Micromeritics*, available at the Environmental Control Laboratory I (LCA), Department of Chemical Engineering (DEQ), Federal University of São Carlos (UFSCar). Physicochemical analyses were conducted at the Structural Characterization Laboratory, Department of Materials Engineering, UFSCar, employing scanning electron microscopy (SEM) to evaluate particle morphology and X-ray fluorescence (XRF) to determine chemical composition.

Two virgin filter media composed of 100% meta-aramid, produced by needle-felt and hydroentanglement, were analyzed. Two samples were collected from each filter medium. Basis weight was determined in triplicate using a semi-analytical balance and a digital caliper (Starrett 727-8/200), in accordance with the NBR 12984 standard (ABNT, 2009). Thickness was measured with a digital thickness gauge (Digimess 130.403), with five measurements taken per sample and the average value reported. Air permeability was evaluated in triplicate using the equipment Testex TF164B, following the ASTM D737-96 standard (ASTM, 2023), which specifies a test area of 38.3 cm² and a pressure differential of 125 Pa.

Filtration tests were conducted using a test filter in accordance with the guidelines specified in the VDI 3926 standard. The equipment is available at the LCA of the DEQ/UFSCar. A schematic representation of the system is shown in Figure 1.

Figure 1 - Test Filter Operating Scheme (VDI, 2004; Vieira et al., 2026).



The normative values established and the phases followed during the filtration tests are presented in Tables 1 and 2.

Table 1 - Standard Values for Filtration Tests (VDI, 2004).

Parameters	Value
Filtration velocity	2 m/min
Concentration of particles in the filter	5,0 g/m ³ ± 10 %
Temperature	20°C – 25°C
Relative humidity	< 50 %
Pressure in the cleaning tank	5 bar ± 3 %
Maximum pressure drop	1000 Pa

Table 2 - Phases for filtration tests (VDI, 2004).

Phases	Conditions
1st phase – Operation of the new filter	30 cycles with pulses controlled by a maximum pressure drop
2nd phase – Artificial aging	10,000 pulses of 5 seconds
3rd phase – Stabilization	10 cycles with controlled pulses
4th phase – Aging filter operation	30 cycles with pulses controlled by a maximum pressure drop

The desulfurization powder was fed into a dust feeder positioned on a balance platform and conveyed into a mixing duct using compressed air. The particle-laden gas stream then passed through the filter medium, which is mounted on a support, where particle collection occurred. The cleaned gas subsequently flowed through a high-efficiency particulate air (HEPA) filter before being released into the environment. At the end of each filtration cycle, the filter medium is cleaned by pulse-jet system using a compressed air reservoir.

Filtration parameters and pressure drop were continuously monitored and recorded using a data acquisition system. Each sample was weighed before and after the filtration tests to determine mass variation. In addition, the absolute (HEPA) filter was weighed to quantify the mass of particles penetrating the filter medium, enabling the calculation of gravimetric collection efficiency. The collection efficiency (η) was determined as the ratio between the mass retained in the test filter (M_{FT}) and the total mass of particles, defined as the sum of the mass retained in the test filter (M_{FT}) and the mass collected in the absolute filter (M_{FA}), as expressed in Equation 1.

$$\eta (\%) = \left(\frac{M_{FT}}{M_{FT} + M_{FA}} \right) \cdot 100 \quad (1)$$

RESULTS AND DISCUSSIONS

The results include the morphological and physicochemical characterization of the particulate material and filter media, as well as the evaluation of filtration performance in terms of the pressure drop, filtration time, and collection efficiency. These analyses enable a direct comparison between the needle-felt and hydroentangled media.

Figure 2 shows SEM images of the particulate material derived from the desulfurization process, highlighting its morphological characteristics. The particles are predominantly observed as agglomerates, with a tendency toward slightly spherical shapes.

Figure 2 – SEM of the particulate from the desulfurization process.

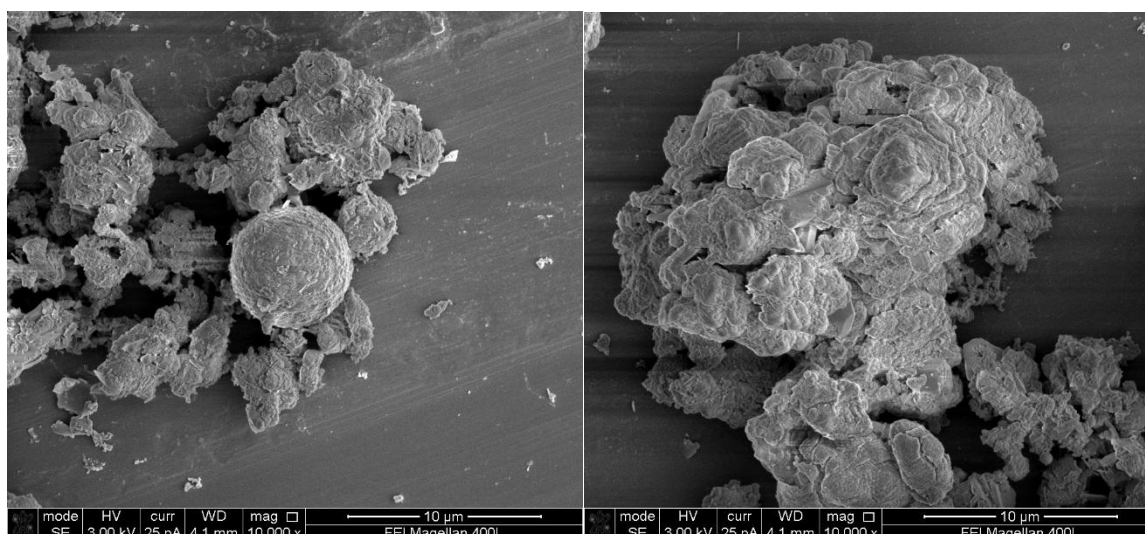


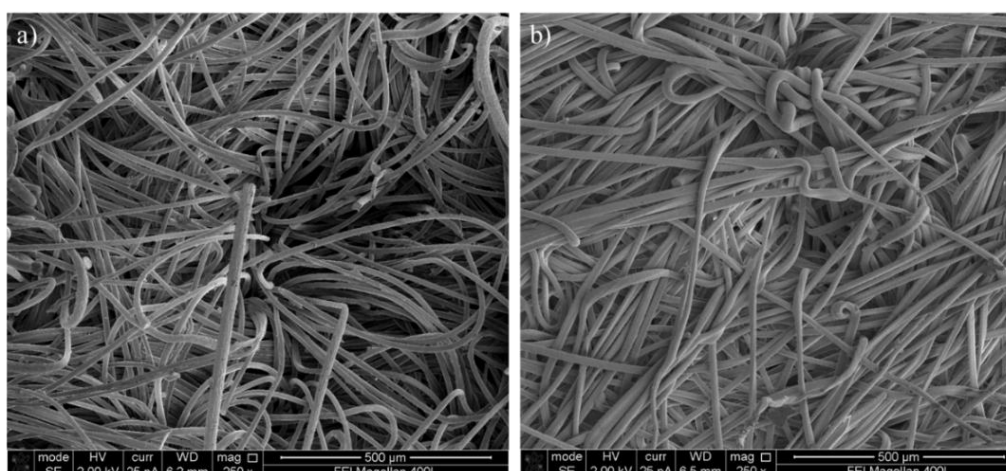
Table 3 summarizes the particle density and chemical composition of the material. The results indicate a heterogeneous composition, with a predominance of calcium (Ca) and iron (Fe), accounting for approximately 59% and 23%, respectively. The presence of these elements is consistent with the typical composition of residues generated during pig iron desulfurization processes and may influence both the physical properties and the filtration behavior of the particulate material.

Table 3 – Desulfurization Powder Characterizations.

Characterizations		Desulfurization Powder
Specific mass (g/cm ³)		2.739 ± 0.002
Chemical Composition (% mass)	Ca	59.069 ± 0.179
	Fe	22.633 ± 0.092
	Cl	0.736 ± 0.066
	K	5.333 ± 0.057
	Others	12.229 ± 0.109

Figure 3 presents SEM images of the analyzed filter media, highlighting differences in fiber arrangement between the two materials. The needle-felt exhibits a heterogeneous structure, characterized by randomly oriented fibers and larger void spaces. In contrast, the hydroentangled shows a more compact and uniform arrangement, with fibers more closely packed and better organized. These structural differences can directly influence permeability and the overall filtration performance of the materials.

Figure 3 - SEM of the fiber of the filter media: needle-felt (a) and hydroentangled (b).



The characterization results of the filter media are presented in Table 4, expressed as the average values obtained from two samples of each material.

Table 4 – Characterization of samples of filter media.

Parameters	Filter media	
	Needle-felt	Hydroentangled
Basis Weight (g/m²)	613.14 ± 0.40	558.81 ± 6.00
Thickness (mm)	2.34 ± 0.03	2.11 ± 0.04
Permeability (cm³/cm².s at 125Pa)	8.98 ± 0.12	8.06 ± 0.59

As indicated by the SEM images, the needle-felt filter medium exhibited higher permeability, which is consistent with its more open and less compact fiber structure. This filter medium also showed slightly higher basis weight and thickness; however, these differences were not significant when compared to the hydroentangled material. The more uniform and compact fiber arrangement observed in the hydroentangled medium likely contributes to its relatively lower permeability. Higher air permeability may lead to improved filtration performance in terms of collection efficiency (Debnath et al., 2020), although this relationship depends on the interaction between airflow conditions and the characteristics of the particulate matter.

The pressure drops as a function of time, obtained during the filtration tests for the first and fourth phases, is presented in Figures 4 and 5. The results correspond to the two samples collected from each filter medium.

Figure 4 - Pressure drop as a function of time for the needle-felt filter medium during the 1st phase (a) and 4th phase (b).

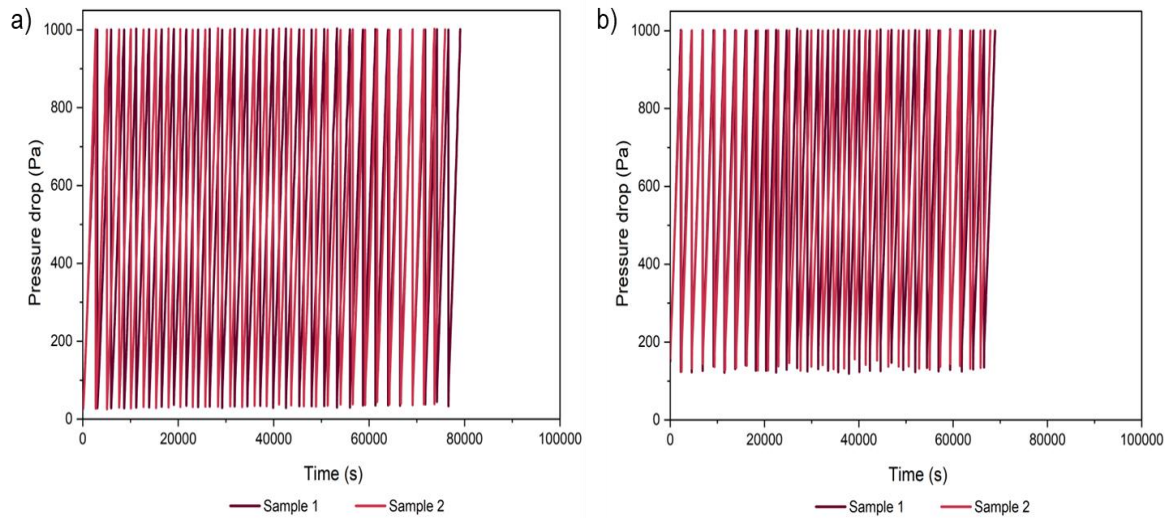
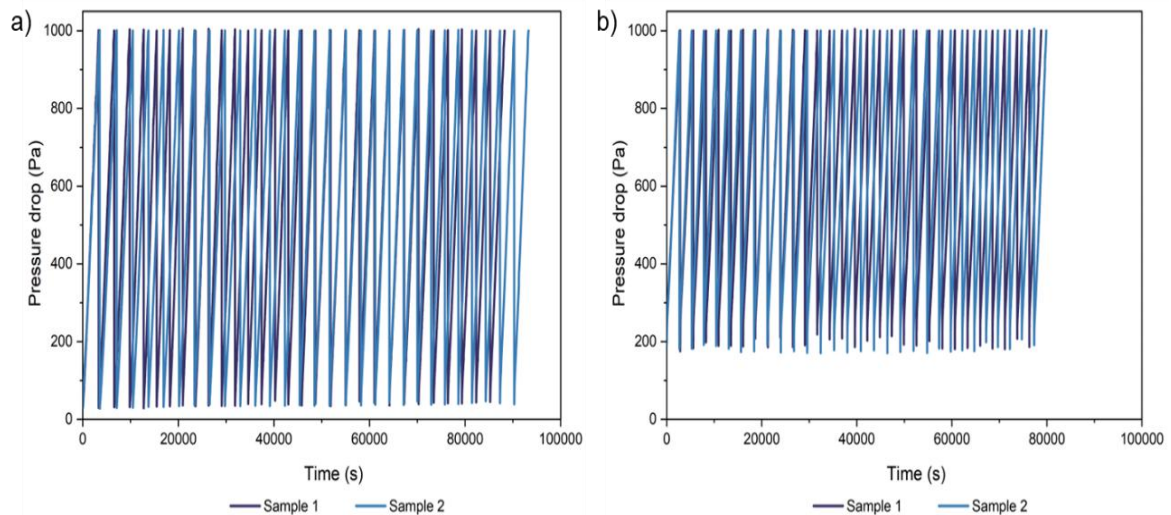


Figure 5 - Pressure drop as a function of time for the hydroentangled filter medium during the 1st phase (a) and 4th phase (b).



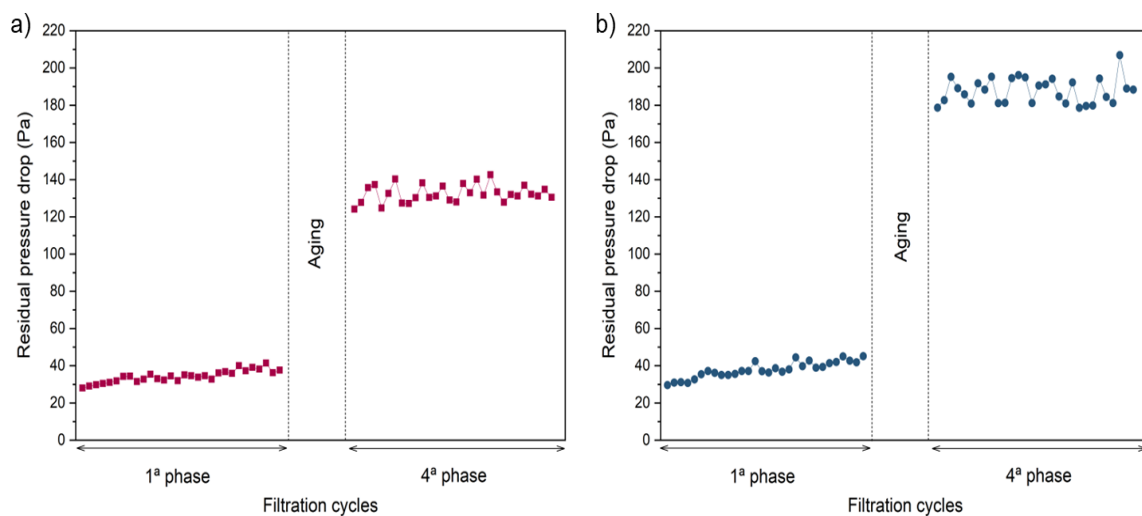
Analysis of Figures 4 and 5 indicates that the hydroentangled filter medium achieved longer total filtration times than the needle-felt medium, even after the aging stage (4th phase). In the first phase, the needle-felt medium reached approximately 79,092 s, while the hydroentangled medium achieved about 90,757 s. In the fourth phase, the needle-felt medium presented a total filtration time of approximately 68,397 s, whereas the hydroentangled medium reached around 79,334 s. This corresponds to a reduction of approximately 13.5% in total filtration time for the needle-felt medium between the 1st and 4th phases, while the hydroentangled medium showed a slightly lower reduction of about 12.6%. These values represent the average of the two samples evaluated for each filter medium.

The longer filtration time observed for the hydroentangled medium indicates a slower rate of pressure drop increase, suggesting more stable filtration cycles and a delayed need for cleaning. This behavior may be associated with its more compact fiber structure, which can promote a more gradual dust cake formation and improved

filtration stability over time. However, despite the longer filtration time in both phases, the hydroentangled filter medium exhibited a higher residual pressure drop, as shown in Figure 6.

The residual pressure drops as a function of filtration cycles, obtained during the tests for the first and fourth phases, are presented in Figure 6. The reported values correspond to the average of the two samples evaluated for each filter medium. Residual pressure drop refers to the pressure loss that remains in the filter immediately after the cleaning process, prior to the formation of a new dust cake (Cirqueira et al., 2019). It is an important parameter for filter media selection and energy consumption and may also influence the operational lifetime of the filter medium (Singh et al., 2023).

Figure 6 – Residual pressure drop as a function of the filtration cycles for needle-felt (a) and hydroentangled (b) filter media.



As previously observed in Figure 5 and more clearly shown in Figure 6, the hydroentangled filter medium exhibited a higher residual pressure drop in the fourth phase, after aging, compared to the needle-felt medium. In the first phase, both filter media showed a similar increasing trend in residual pressure drop throughout the filtration cycles, with only minor differences, as the hydroentangled medium presented slightly higher values.

In the fourth phase, both filter media exhibited significant variations in residual pressure drop across the filtration cycles, including pronounced peaks. This behavior is commonly referred to as “patch cleaning,” in which the cleaning pulse does not remove the dust cake uniformly, leaving some regions clean while others remain loaded. Such non-uniform cleaning can significantly affect residual pressure drop, particle emissions, and the operational lifetime of the filter medium (Li et al., 2024; Tanabe et al., 2011; Xie et al., 2022). This irregular cleaning behavior may also be associated with filter heterogeneity, particle size distribution, and variations in the chemical composition of the gas and dust, particularly under high-temperature conditions (Duo et al., 1997). In addition, strong dust adhesion can hinder removal in certain regions, leading to incomplete regeneration and increased pressure drop even under standard pulse-jet cleaning conditions (Li et al., 2023a).

The hydroentangled filter medium showed a greater tendency to develop resistance after aging, resulting in higher residual pressure drop. This behavior is likely

associated with its more compact structure, lower permeability, and increased dust retention within the fiber network. However, despite exhibiting a higher residual pressure drop, the hydroentangled filter medium achieved longer filtration times.

An increase in pressure drop across bag filters requires the downstream fan to consume more energy to maintain the desired airflow conditions (Park et al., 2019). This effect can be intensified by factors such as high humidity and fine particle size, which promote deeper particle penetration into the filter medium and agglomeration phenomena, leading to increased flow resistance and, consequently, higher residual pressure drop (Li et al., 2023c, 2023b).

The collection efficiency results, calculated by equation 1, indicate that both filter media achieved high performance in all tested phases. Considering the average of the two samples for each material, the hydroentangled filter medium presented efficiencies of $99.97\% \pm 0.03$ in the first phase and $99.99\% \pm 0.01$ in the fourth phase. For the needle-felt filter medium, the average efficiencies were $99.98\% \pm 0.01$ in the first phase and $99.94\% \pm 0.04$ in the fourth phase. Statistically, no significant differences were observed between the filter media or across the evaluated phases. Overall, both materials maintained collection efficiencies above 99.9%, demonstrating stable and highly effective filtration performance, with only minor variations after the aging process.

Fukasawa et al. (2021) evaluated three commercially available nonwoven filter media made of polytetrafluoroethylene (PTFE) and reported that higher filtration efficiency and lower particle emission rates are associated with filters exhibiting greater basis weight and lower air permeability. Similarly, Singh et al. (2023) reported that dust emissions, residual pressure drop, and dust penetration depth are lower for needle-felt membrane filter media compared to other filter media types. The authors also observed that the tendency of the filter media to clog can contribute to increased residual pressure drop. Furthermore, needle-felt polyester filter media showed a greater reduction in dust penetration for particles such as aluminum fluoride and fly ash, attributed to the lower density and cohesion of fly ash which favor the formation of a more uniform and compact dust layer on the filter surface, improving filtration efficiency, although potentially increasing pressure drop.

Based on these findings, and as also observed in the present study, it is essential to consider the properties of the particulate material, as the performance of each filter medium is heavily influenced by the specific characteristics of the dust being filtered.

CONCLUSION

The characterization results showed that the particulate material presents a heterogeneous composition and an agglomerated morphology. The filter media exhibited distinct structural features, with the needle-felt filter medium being more permeable and the hydroentangled filter medium more compact. These structural differences directly influence filtration behavior.

Both filter media demonstrated high collection efficiency ($>99.9\%$) under all tested conditions, with no statistically significant differences observed between them. However, differences in operational behavior were observed. The hydroentangled filter medium exhibited longer filtration times, indicating more stable filtration cycles and a slower rate of pressure drop increase, even after aging. In contrast, it showed higher residual pressure drop, suggesting greater airflow resistance, likely associated with its more compact structure and increased dust retention.

Overall, although both filter media are effective in particle removal, their performance is strongly influenced by their structural characteristics and interaction with the particulate material. Therefore, the selection of filter media should consider not only efficiency but also operational parameters such as pressure drop, cleaning behavior, filter lifetime, dust penetration tendency, particle properties, and filtration conditions.

ACKNOWLEDGEMENTS

The authors would like to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), process no. 195812/2025-5, the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, and ArcelorMittal for their financial support and supply of materials for this research.

REFERENCES

- ABNT, 2009. NBR 12984 - Não tecido - Determinação da massa por unidade de área [WWW Document]. Norma Bras. URL <https://www.target.com.br/produtos/normas-tecnicas/35904/nbr12984-naotecido-determinacao-da-massa-por-unidade-de-area> (accessed 11.1.23).
- ASTM, 2023. Test Method for Air Permeability of Textile Fabrics. ASTM Int. <https://doi.org/10.1520/D0737-18R23>
- Bhatti, U.A., Yan, Y., Zhou, M., Ali, S., Hussain, A., Qingsong, H., Yu, Z., Yuan, L., 2021. Time Series Analysis and Forecasting of Air Pollution Particulate Matter (PM 2.5): An SARIMA and Factor Analysis Approach. IEEE Access 9, 41019–41031. <https://doi.org/10.1109/ACCESS.2021.3060744>
- Cirqueira, S.S.R., Tanabe, E.H., Aguiar, M.L., 2019. Experimental investigation of particle deposition in filter media during filtration cycles with regeneration by pulse jet cleaning. Process Saf. Environ. Prot. 127, 288–298. <https://doi.org/10.1016/j.psep.2019.05.013>
- Debnath, S., Chauhan, V.K., Singh, J.P., 2020. Air permeability of needle-punched filter media—virgin and recycled polyester. J. Text. Inst. 111, 1159–1165. <https://doi.org/10.1080/00405000.2019.1688906>
- Donovan, R.P., 1985. Fabric Filtration for Combustion Sources: Fundamentals and Basic Technology, 1st ed. ed. Marcel Dekker, New York.
- Duo, W., Kirkby, N.F., Seville, J.P.K., Clift, R., 1997. Patchy cleaning of rigid gas filters—I. A probabilistic model. Chem. Eng. Sci. 52, 141–151. [https://doi.org/10.1016/S0009-2509\(96\)00370-3](https://doi.org/10.1016/S0009-2509(96)00370-3)
- El Messiry, M., Al-Oufy, A., Elmor, M., 2024. Investigations of the recycling of airbag filters from the cement industry into fabric/polymer or fabric/cement composite materials. Discov. Appl. Sci. 6, 42. <https://doi.org/10.1007/s42452-024-05632-8>
- Fukasawa, T., Kanaoka, C., Kimura, I., Bao, L., Ishigami, T., Fukui, K., 2021. Distributions of Fiber Mass, Air Permeability, and Filter Efficiency in Nonwoven Fabric Bag Filters. Chem. Eng. Technol. 44, 535–541.

<https://doi.org/10.1002/ceat.202000472>

- Hutten, I.M. (Ed.), 2016. Handbook of nonwoven filter media, 2nd Editio. ed. Butterworth-Heinemann, Massachusetts, USA.
- Karthik, T., C., P.K., Rathinamoorthy, R., 2016. Nonwovens: Process, structure, properties and applications, 1st ed. Woodhead Publishing India Pvt. Ltd., New Delhi.
- Li, J., Chen, D.-R., Li, S., Zhou, F., 2024. Reverse pulsed-flow cleaning for filtration unit regeneration: A review. *Sep. Purif. Technol.* 330, 125441. <https://doi.org/10.1016/j.seppur.2023.125441>
- Li, S., Cheng, H., Hu, S., Wen, G., Zhou, A., Gui, C., Yuan, L., Zhou, F., 2023a. Study on the influence of built-in open-hole dust cleaner on the cleaning performance of cartridge filter. *Process Saf. Environ. Prot.* 173, 786–799. <https://doi.org/10.1016/j.psep.2023.03.054>
- Li, S., Liu, L., Tan, X., Liu, H., Gui, C., Chen, X., Han, M., Lin, Y., Shao, J., Yuan, L., Zhou, F., 2023b. Effects of filter cartridge wetted before filtration and during filtration on the performance of cartridge dust collector. *Process Saf. Environ. Prot.* 177, 169–176. <https://doi.org/10.1016/j.psep.2023.07.008>
- Li, S., Wen, G., Lv, W., Liu, H., Lin, Y., Yuan, L., Zhou, F., 2023c. Effects of various humid environments on the filtration and dust cleaning performance of filter media. *Sep. Purif. Technol.* 309, 122940. <https://doi.org/10.1016/j.seppur.2022.122940>
- Liu, X., Shen, H., Nie, X., 2019. Study on the Filtration Performance of the Baghouse Filters for Ultra-Low Emission as a Function of Filter Pore Size and Fiber Diameter. *Int. J. Environ. Res. Public Health* 16, 247. <https://doi.org/10.3390/ijerph16020247>
- Matteson, M.J., Orr, C., 1987. Filtration: Principles and Practices, 2nd ed. ed. Marcel Dekker, New York.
- Park, S., Joe, Y.H., Shim, J., Park, H., Shin, W.G., 2019. Non-uniform filtration velocity of process gas passing through a long bag filter. *J. Hazard. Mater.* 365, 440–447. <https://doi.org/10.1016/j.jhazmat.2018.10.098>
- Ramon, M., Ribeiro, A.P., Theophilo, C.Y.S., Moreira, E.G., de Camargo, P.B., de Bragança Pereira, C.A., Saraiva, E.F., dos Reis Tavares, A., Dias, A.G., Nowak, D., Ferreira, M.L., 2023. Assessment of four urban forest as environmental indicator of air quality: a study in a brazilian megacity. *Urban Ecosyst.* 26, 197–207. <https://doi.org/10.1007/s11252-022-01296-7>
- Russell, S.J., 2022. Handbook of Nonwovens, 2nd ed. Woodhead Publishing.
- Schraufnagel, D.E., Balmes, J.R., Cowl, C.T., De Matteis, S., Jung, S.-H., Mortimer, K., Perez-Padilla, R., Rice, M.B., Riojas-Rodriguez, H., Sood, A., Thurston, G.D., To, T., Vanker, A., Wuebbles, D.J., 2019. Air Pollution and Noncommunicable Diseases. *Chest* 155, 417–426. <https://doi.org/10.1016/j.chest.2018.10.041>

- Singh, P., Mukhopadhyay, A., Gupta, P., 2023. Performance of surface finished polyester filter media exposed to different dust types with the variation of dust concentration. *Powder Technol.* 426, 118614. <https://doi.org/10.1016/j.powtec.2023.118614>
- Sutherland, K., 2008. *Filters and Filtration Handbook*, 5th ed. ed. Elsevier, MA, USA.
- Tanabe, E.H., Barros, P.M., Rodrigues, K.B., Aguiar, M.L., 2011. Experimental investigation of deposition and removal of particles during gas filtration with various fabric filters. *Sep. Purif. Technol.* 80, 187–195. <https://doi.org/10.1016/j.seppur.2011.04.031>
- Thangavel, P., Park, D., Lee, Y.-C., 2022. Recent Insights into Particulate Matter (PM_{2.5})-Mediated Toxicity in Humans: An Overview. *Int. J. Environ. Res. Public Health* 19, 7511. <https://doi.org/10.3390/ijerph19127511>
- VDI, 2004. VDI 3926: Testing of filter media for cleanable filters Standard test for the evaluation of cleanable filter media [WWW Document]. Düsseldorf. Verein Dtsch. Ingenieure. URL <https://www.vdi.de/en/home/vdi-standards/details/vdi-3926-blatt-1-testing-of-cleanable-filter-media-standard-test-for-the-evaluation-of-cleanable-filter-media> (accessed 11.9.22).
- Vieira, A.C.C., Chagas, P.A.M., Sartim, R., Aguiar, M.L., 2026. Impact of aging on the efficiency and service life of filter bags in the steel industry. *Sep. Purif. Technol.* 382, 136166. <https://doi.org/10.1016/j.seppur.2025.136166>
- Wei, Y., Wang, Yan, Di, Q., Choirat, C., Wang, Yun, Koutrakis, P., Zanobetti, A., Dominici, F., Schwartz, J.D., 2019. Short term exposure to fine particulate matter and hospital admission risks and costs in the Medicare population: time stratified, case crossover study. *BMJ* l6258. <https://doi.org/10.1136/bmj.l6258>
- WHO, 2023. WHO ambient air quality database, 2022 update [WWW Document]. World Heal. Organ. URL <https://iris.who.int/bitstream/handle/10665/368432/9789240047693-eng.pdf?sequence=1> (accessed 11.28.23).
- WHO, 2021. WHO global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide [WWW Document]. World Heal. Organ. URL <https://www.who.int/publications/i/item/9789240034228> (accessed 11.15.22).
- WHO Regional Office for Europe (Ed.), 2026. *Air quality indexes: key considerations and roadmaps for best practices*. Copenhagen.
- Xie, B., Pang, J., Hu, S., Zhou, Z., Jin, H., 2022. A new method to improve the pulse-jet cleaning performance of filter cartridges and its application to dust control in underground coal mines. *Powder Technol.* 405, 117528. <https://doi.org/10.1016/j.powtec.2022.117528>
- Zhou, G., Low, Z.-X., Feng, S., Zhang, F., Zhong, Z., Xing, W., 2023. Effect of relative humidity and dust moisture content on filtration performance of bag filter. *Sep. Purif. Technol.* 308, 122952. <https://doi.org/10.1016/j.seppur.2022.122952>