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A Theoretical Reliability Framework for Segmented Particulate Filters in Industrial Chimneys

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Abstract

Industrial chimney particulate filters are used to reduce the release of harmful particles into the atmosphere. However, conventional single-filter systems are vulnerable to clogging and single-point failures, reducing filtration reliability. This paper proposes a segmentation technique to improve filter reliability without increasing the total filter volume or filter material. A theoretical reliability analysis was conducted to evaluate the proposed design. Assuming an individual filter reliability of 80%, the segmented configuration achieves a theoretical system reliability of 89.6%, representing a 12% improvement over a conventional single-filter system. The proposed segmented configuration is intended to improve system reliability through modularisation, and the reliability analysis provides a theoretical proof-of-concept framework. Experimental validation through pressure-drop analysis, airflow modelling, and particle collection efficiency testing is recommended for future work. The proposed approach provides a theoretical framework for investigating segmentation as a reliability-enhancement strategy for industrial chimney particulate filtration systems.

Keywords: Particulate filtration; industrial chimneys; segmentation technique; reliability analysis; modular filters; risk reduction

Introduction

Industrial chimney particulate filters are designed to remove suspended solid particles, such as dust, ash and soot, from exhaust gases before they are released into the atmosphere. These systems differ from technologies used for carbon dioxide capture or gaseous pollutant absorption, which rely on different physical and chemical mechanisms. Carbon monoxide (CO) significantly influences global air chemistry (Rasmussen & Khalil,1984). The issue of environmental pollution caused in part by toxic particles from industrial factories and power plant chimneys is urgent. Since the Industrial Revolution in the 19th century, concerns about air pollution resulting from factories and the emission of toxic smoke from chimneys across Europe have grown. Engineers, town planners, and lawmakers are focused on this problem (Scorer & Barrett, 1962). Factories and power plants now play a major role in the overall pollution cost to the Earth. A study by the US Environmental Protection Agency (2026) reports that electricity production and industry in the U.S. account for 25% and 23% of CO_2 and other greenhouse gas emissions, respectively. Burning hydrocarbon fuels like coal has increased atmospheric CO_2 levels and other greenhouse gases, altering the natural composition of atmospheric gases. This change affects global radiation and heat balance by increasing sensible heat in the air. Solar radiation can reach Earth's surface while outgoing terrestrial long-wave radiation is partly trapped, leading to shifts in weather patterns and climate on global and regional scales. These changes can severely impact plant and animal life, resulting in ecological imbalances.

Research indicates that pollution-related respiratory illnesses and allergies, such as asthma, are increasing significantly (Figure 1). These chemical-related diseases cause approximately 7 million premature deaths worldwide each year (World Health Organisation, 2025). Factories implement "end-of-pipe " technologies to reduce the emission of toxic particles into the air, a practice that began in the 1960s with the Clean Air Act and has been continuously improved to meet stricter standards (NESTEC, 2018). Nonetheless, further advancements are needed. One promising solution involves multi-layer filters that target harmful pollutants, reducing particles released into the atmosphere. This approach could decrease illnesses and pollution, while the captured toxic waste could be safely removed and repurposed.

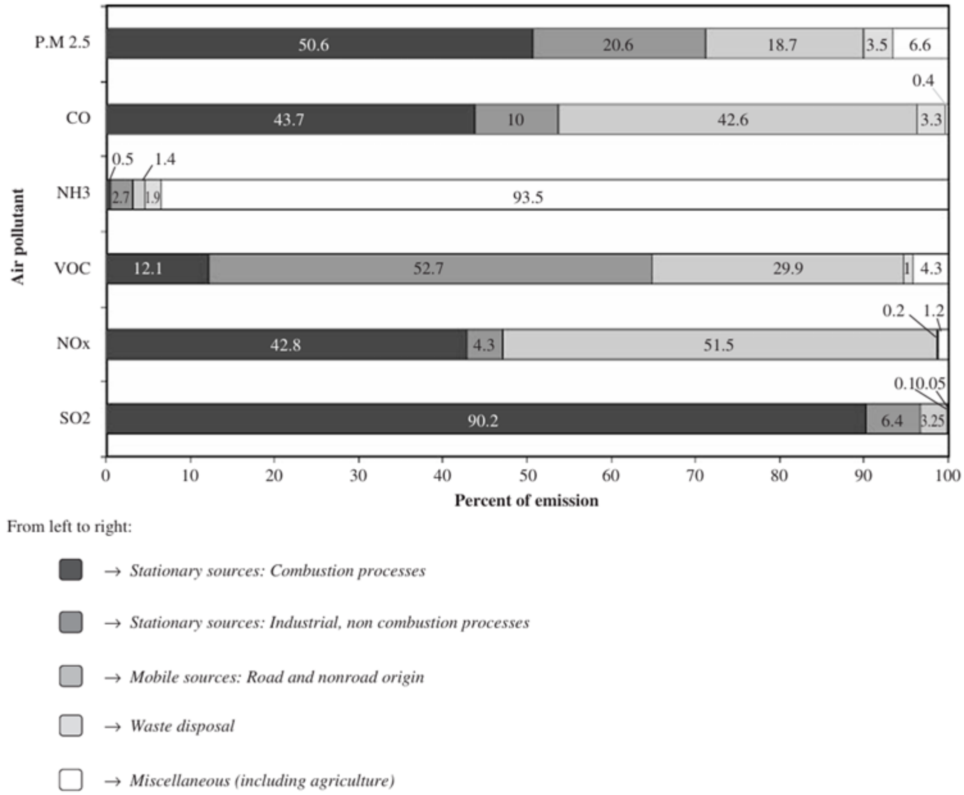


Figure 1: Distribution of EU-27 total emission estimates for different pollutants, by source category, in 2006 (Kennes & Veiga, 2013)

This study proposes a theoretical reliability framework for segmented particulate filters used in industrial chimneys. The objective is to investigate whether a modular filter configuration can improve system reliability while maintaining the same total filter material. The study does not experimentally evaluate pressure drop, filtration efficiency or industrial operating performance. Despite this, particle emissions remain relatively high. Segmentation is investigated as a reliability strategy rather than a demonstrated method for increasing particle collection efficiency. The chosen risk management strategy of segmentation doesn't rely on external sources to lower risks (Todinov, 2018). In this system, segmentation reduces risk by adding additional filters within the chimney, positioned directly toward the outlet, maximising particle capture. This approach also keeps upgrade costs low since modifications are confined to the existing chimney system, minimising further investment.

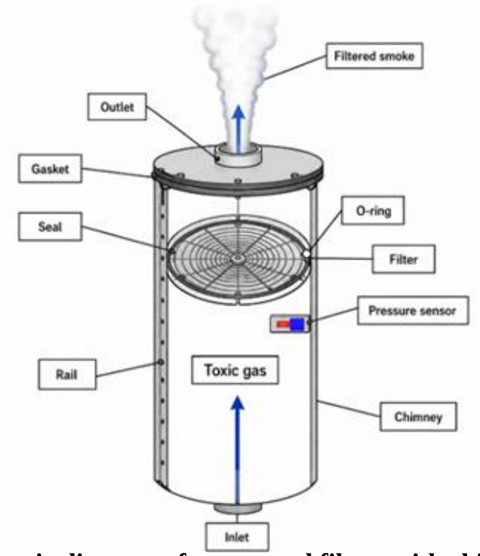
Gas filter system structure and failure modes

Gas filter structure

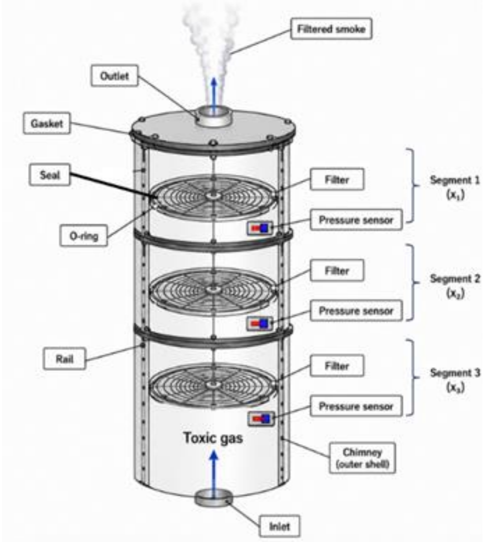
Understanding the gas filter structure and its components is essential for quickly identifying critical failures and detecting potential issues early. Figures 2 (a, b) illustrate the gas filter structure and its components before and after the segmentation method application.

Fig. 2: Comparison of the conventional and proposed segmented gas filter configurations

Schematic diagram of original gas filter



Schematic diagram of segmented filters with chimney



Note: The proposed segmented configuration is intended only as a theoretical reliability framework. The total filter material is assumed to remain constant by dividing one filter of thickness $t$into three modules of thickness $t/3$. This assumption does not imply identical pressure drop, airflow distribution, particle collection efficiency, or dust holding capacity. These engineering characteristics depend on operating conditions and require future experimental validation.

Potential Failure Modes of Filter

The gas filter system includes various components, each with potential failure modes. Common issues include:

- Seal and gasket deterioration, which can cause gas leaks and reduce filter efficiency. [Solution: Upgrade sealing technology by replacing seals and gaskets with high-quality materials to improve durability and resistance to gas exposure.]
- Malfunctioning pressure sensors. [Solution: Regularly calibrate sensors to ensure accuracy, and review software settings and configurations for sensor interfaces.]
- Erosion of filter media. [Solution: Use durable media resistant to damage from harsh fluids and abrasive particles.]
- Extreme temperatures affecting O-rings, leading to sealing failures. [Solution: Implement heat insulation to protect O-rings from temperature extremes.]
- Filter clogging or blocking. [Solution: Optimise flow rates to maintain the recommended gas flow, as excessively high flow rates can embed particles into the filter media, causing clogging.]

Figure 3 below shows typical gas filtration and gas clogging mechanisms.

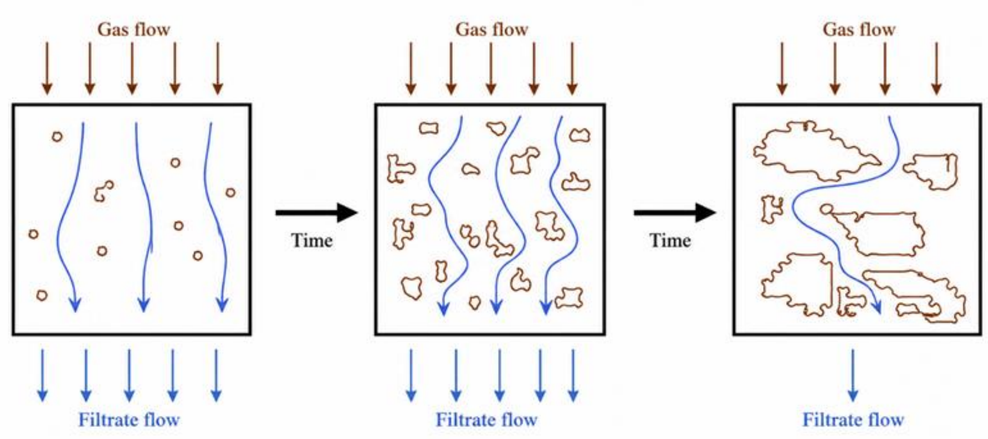


Figure 3: Typical filtration and gas clogging mechanism

Enhancing Gas Filter Reliability through Segmentation Technique

The segmentation method is essential to consider in the reliability field; this method is implemented here to be used to segment the gas filter into small partial filters rather than a single one. Figure 4 (4a, 4b) below shows the schematic visualisation of the applied segmentation method on the gas filter system.

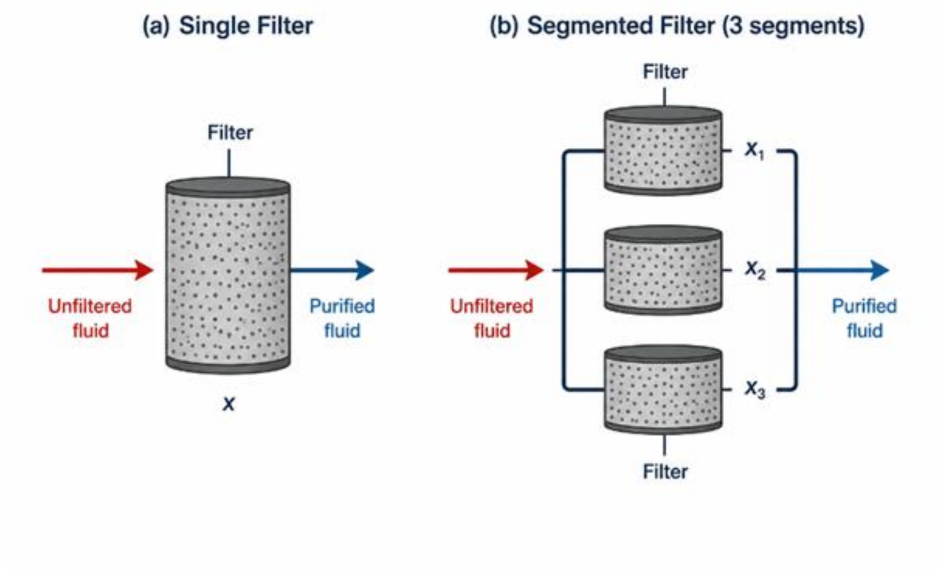


Figure 4: Schematic illustration of the conventional and segmented filter designs (Todinov, 2023; Todinov, 2026)

To clarify the effectiveness of the segmentation method, suppose that the reliability of a filter working is R = 0.8. Therefore, the reliability of a single filter working is 0.80 (80%). Applying the same approach to the segmented filters, the reliability is summarised in Table 2 below.

Reliability assumptions

The theoretical reliability analysis is based on the following assumptions:

- The three filter modules are identical.
- Failures occur independently.
- Exhaust flow is equally distributed among the filter modules.
- A failed module can be isolated without significant bypass leakage.
- The remaining modules continue to satisfy the required exhaust-flow rate and filtration requirements.
- The analysis evaluates system reliability only and does not represent experimentally verified filtration performance.

For the purpose of the theoretical reliability analysis, a filter module is considered to have failed when it is unable to maintain the required operating conditions because of excessive clogging, unacceptable pressure drop, structural damage, or loss of filtration capability. Quantitative failure thresholds, clogging rates, and maintenance intervals are outside the scope of this study and require further experimental investigation.

Table 2: Theoretical reliability analysis of the proposed three-segment filter system

Operating condition	Reliability expression	Calculation (R = 0.8)	Reliability
All three segments are operational	R^3	$(0.8)^3 = 0.512$	0.512 (51.2%)
Exactly two segments are operational	$3R^2(1-R)$	$3(0.8)^2(1-0.8)$ $= 0.384$	0.384 (38.4%)
Overall segmented-system reliability (at least two segments remain operational)	$R_{\text{segmented}} = R^3 + 3R^2(1-R)$	$0.512 + 0.384 = 0.896$	0.896 (89.6%)

In this study, the system is assumed to remain operational when at least two of the three filter modules continue to function. This assumption is based on the conceptual premise that the remaining two modules are capable of maintaining the minimum required exhaust-flow capacity, acceptable particulate-removal efficiency, and allowable pressure-drop limits. Since the present study is theoretical, quantitative failure thresholds, clogging rates, bypass flow, pressure-drop limits, and maintenance intervals are not defined and should be established through future experimental and industrial investigations. Therefore, the two-out-of-three operating criterion is adopted solely to illustrate the reliability benefits of the proposed segmentation concept.

Therefore, it can be compared between conventional and segmented filter systems to evaluate how reliability is improved by the following methods :

$$\frac{R_{\text{segmented}} - R_{\text{single}}}{R_{\text{single}}} \times 100 = \frac{89.6 - 0.80}{0.80} = 12\%$$

Under the assumptions adopted in this theoretical analysis, the calculated system reliability increases from 0.80 to 0.896. This result represents an improvement in theoretical system reliability and should not be interpreted as an experimentally verified increase in filtration efficiency.

The segmentation method manages failure modes and minimises the risk of a single failure by dividing the entity into smaller, distinct parts, as shown above (Todinov, 2023). This approach not only helps to reduces the consequences of a single module failure through modular system architecture, but it also may distribute dust loading more uniformly among the modules; however, this hypothesis requires experimental confirmation, thereby improving the overall effectiveness of the filtration process.

Studying gas filter system behaviour is essential for understanding the filter model's characteristic curve. The collected particle efficiency through the filter is illustrated in Figure 5 (Fu et al., 2010).

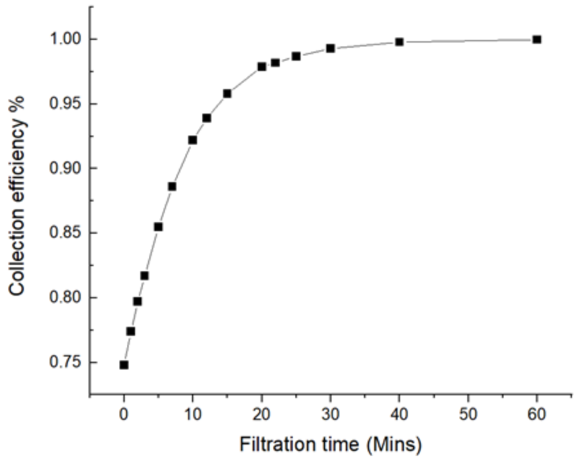


Figure 5: Collection efficiency (%) vs. filtration time (Fu et al., 2010)

The behaviour of the gas filter efficiency within filtration time seems to be a concave curve; hence, we can induce more to it with the properties of concave power laws.

The above scenario can be optimized using algebraic inequalities by inducing concave power laws for the sub-additive inequalities. Given that the original gas filter has the following concave function expression:

$$\mathrm{F}(x) = ax^{m} \rightarrow [1]$$

Where a is a constant $a > 0$ and m is the power of the controlling factor x, the output F(x) decreases as x increases. To consider the concavity of this function, the power m should be constrained in the range $0 < m < 1$, as the second derivative of the above function with these conditions would be a concave function. Hence, in our case, the generic representation of the concave power law function would be the following, as shown in Figure 6.

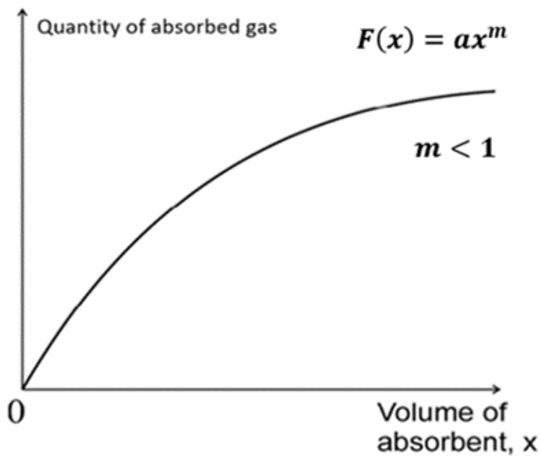


Figure 6: Concave power-law representation (Todinov, 2023)

F(x) represents the amount of gas absorbed, with x indicating the absorbent volume. Since absorption capacity saturates at larger absorbent volumes, the exponent b is less than one, as shown earlier. By segmenting the volume of the original filter x into small volumes (x_A, x_b and x_c) through which gas is filtered is ($x = x_A + x_b + x_c$); Therefore, that would result in the following absorbed quantities.

$$F_A = ax_A^m\,; F_b = ax_b^m\,; F_c = ax_c^m$$

By now, applying knowledge of interpreting algebraic inequalities (Todinov, 2023), it can be shown that, for $m < 1$, the following inequalities will hold:

$$ax^m < ax_a^m + ax_b^m + ax_c^m \quad \rightarrow [2]$$

Equation (2) provides a mathematical interpretation of segmentation based on concave power-law behaviour. It should not be interpreted as experimental evidence of increased particle collection or gas absorption, more than an individual gas filter. Additionally. Segmenting the filter also boosts reliability by:

1. Improving system robustness through modular filter architectureby using partitioned, smaller filter sections.
2. Decreasing the risk of impurity in gases through smaller filter units.
3. Minimising risks by simplifying the filter into smaller parts.
4. Enhancing toxic gas filtration efficiency by distributing gases across multiple filters to optimise the process.

Overall, this approach reduces and mitigates toxic gas emissions, lessening their environmental harm.

Solutions to mitigate filter failures

The Filter system can face sudden failures due to external factors, such as high pressure, thermal stresses, or changes in exhaust gas composition, which may introduce new pollutants the filter cannot capture. To address these issues, several mitigation tools can be implemented:

- Investing in advanced filter media technology to prevent clogging and improve gas capture capacity.
- Implementing predictive maintenance to avoid unplanned outages and reduce operational costs.
- Upgrading sealing technology with high-quality materials resistant to gas exposure.
- Incorporating energy–efficient cleaning mechanisms using low-energy solenoids and sensors to lower energy use.
- Installing sensors for remote monitoring of filter performance, pressure differential, and cleaning cycles, connected to a central

control system. Automation can further optimise operations based on real-time data.

These solutions aim to enhance filter reliability without significantly increasing weight, energy consumption, or space. They are cost-effective and strike a good balance between operational expenses and improved system dependability.

Limitations

This study presents a theoretical reliability framework and does not include laboratory experiments, computational fluid dynamics (CFD) simulations, or industrial operating data. Consequently, no conclusions are drawn regarding pressure drop, airflow distribution, dust loading, filtration efficiency, clogging behaviour, or maintenance intervals. The reliability calculations are valid only under the assumptions described in this study, including independent module failures and the adopted two-out-of-three operating criterion. Future research should experimentally compare conventional and segmented filter configurations through pressure-drop measurements, particle collection efficiency tests, dust-loading experiments, maintenance analysis and industrial field validation.

Conclusion

This paper presented a theoretical reliability framework for improving the reliability of industrial chimney particulate filters through the application of a segmentation technique. The proposed approach divides the filter into modular segments while maintaining the same total filter material and volume. Under the assumptions adopted in this study, the theoretical reliability analysis demonstrated a 12% increase in system reliability when the reliability of an individual filter segment was assumed to be 80%. These findings indicate the potential of segmentation as a reliability-enhancement strategy for modular filtration systems. Further experimental and numerical studies are required to validate the effects of the proposed configuration on airflow distribution, pressure drop, particle collection efficiency, dust loading, and long-term operational performance. Overall, the proposed framework provides a basis for future research into the design of more reliable industrial chimney particulate filtration systems.

Conflict of Interest: The author reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

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