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TECHNOLOGY AND CONSTRUCTIVE MODIFICATION OF FILTERING LAYER BASED ON HEAT-RESISTANT BASALT FIBER

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Abstract: This paper presents a design-oriented and technology-focused analysis of forming a heat-resistant basalt fiber–based filtering layer for high-temperature, abrasive cement dust–gas flows. Building on global industrial experience and theoretical reasoning (without reporting experimental measurements), the study frames filtration performance as an integrated material–structure–regeneration system. A gradient (multi-layer) filtering architecture is substantiated, typically composed of a prefilter layer, a main basalt-fiber filtering layer, and a support/protection layer. The approach targets stabilization of pressure-drop growth and improved pulse-jet cleanability by controlling dust cake formation. Needle-punched basalt nonwoven structures are justified as a mechanically robust option under repeated pulse-jet loading, while optional hydrophobic and antistatic surface treatments are discussed as measures to reduce moisture-related cementation and electrostatic adhesion, thereby improving cake release. The main outcome is a calculation-based technological platform that links key filtration objectives (efficiency, pressure stability, cleanability, and durability) to controllable structural parameters of basalt-fiber media and provides a solid basis for subsequent laboratory and industrial validation.
Keywords: basalt fiber, heat-resistant filtration media, cement dust, baghouse filtration, gradient (multi-layer) structure, needle-punched nonwoven, dust cake resistance

Introduction

The cement industry is one of the largest dust-emitting industries in the world, and the fineness of the particle fraction composition in the process gases, the high temperature of the flow and the abrasiveness of the dust create very strict operational requirements for dust collection systems. In world experience, baghouse/fabric filters are considered one of the most effective solutions for dry gas cleaning: the EU BAT conclusions for cement, lime and MgO production aim to maintain dust emissions in the low mg/Nm³ range, and high-efficiency filtration and stable regeneration modes are indicated as decisive factors in achieving this level. In line with this, the US EPA's AP-42 documents for Portland cement production also emphasize the widespread use of baghouse systems in practice for PM emissions management in process areas and the need to correctly select filtration modes and control parameters during design. UNIDO's BAT materials in the cement sector also analyze emission sources and control technologies along the production chain, identifying the “process-equipment-control” integration as the primary approach when choosing modernization and technical solutions.
However, global practice shows that the efficiency of a dust collector filter is determined not only by the choice of “which filter is installed”, but also by the combination of the thermal and mechanical stability of the filter medium, the formation of a cake (dust layer) and the pulse-jet

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regeneration conditions. In high-temperature and aggressive environments, glass fiber or polymer-based filter media may have certain limitations; in this regard, basalt fiber, which belongs to the mineral fiber class, is considered a promising alternative. The results presented by Medvedev and Tsybulya on basalt composite filter fabrics indicate that basalt-based filters can be used for cleaning corrosive/hot gases and are suitable for operation in flows with very hot particles. In recent years, scientific reviews on the prospects of basalt fiber filter media (including the suitability of basalt media for high-temperature filtration and its suitability for repulsive cleaning) indicate basalt fiber as a practically significant material in the "heat-resistant filtration" segment. In addition, the expansion of the approach to assessing efficiency depending on particle size in the ISO 16890 standard for ventilation filters (by PM fractions) means that the concept of "fractional efficiency" in evaluating filter elements is gaining global traction; this also increases the need for media that provide stable capture of fine particles in industrial filtration [1-5].

In Uzbekistan, local studies are also being conducted on the relationship between the composition of dust gases, dust dispersion and cleaning efficiency in cement production plants; these studies indicate problematic points regarding the properties of dust and the operation of existing cleaning devices. At the same time, the potential of basalt fibers to improve filtration is also discussed in the works with the participation of Uzbek authors on the filtration of industrial gases through basalt filtering material. Thus, at the intersection of world experience and local needs, the following scientific and practical gap is clearly visible: it is necessary to develop a basalt fiber filtering layer for filtration in a high-temperature cement dust environment, to scientifically substantiate the structural (multi-layer/gradient) formation and technological solutions that ensure operational stability as a system.

The purpose of this article is to reveal the logic of choosing basalt fiber in the creation of heat-resistant filtering media for the cement industry, based on world experience, to describe the scientific and technical approach to the formation of basalt fiber layers (for example, needle-punched nonwoven structure, multilayer/gradient architecture, modification treatments suitable for thermal and humidity conditions), and to justify the evaluation criteria (aerodynamic resistance, cake management, regenerability and resource) for subsequent tests. The expected scientific result of this approach is to form a technological platform that considers the filtering layer not at the "material" level, but at the "material-structure-regeneration" integration, ensuring stable operation in conditions of high temperature and abrasive dust; practical results are expected to be quantitatively confirmed by further laboratory and industrial tests.

Literature review

World experience in the treatment of dust-gas flows in the cement industry shows that achieving high efficiency is determined not only by the "choice of the type of device", but also by the combination of the structure of the filtering medium, the formation of the dust layer (cake) and the regeneration mode. In particular, the BAT conclusions of the European Union for the production of cement, lime and MgO aim to maintain dust emissions in the low mg/Nm³ range, and fabric filters (baghouse/fabric filters) and their proper operation (stable regeneration, pressure loss control) are considered the most optimal technical approach to achieve this result. In this regard, the US EPA's practical and technical documents on cement production also highlight the widespread use of baghouse systems in PM emission control, the filtration rate (air-to-cloth), cake filtration mode and cleaning cycles as the basic design factors; these

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documents indicate the need for conservative selection of parameters even at the design stage and subsequent optimization with testing. In scientific research, the factors affecting the specific resistance of the cake and the dynamics of pressure drop have been studied in depth: for example, Cheng (1998) linked the effect of the dust layer on the pressure drop with the filtration rate and cake properties, showing that the increase in ΔP is mainly "controlled" by the cake parameters. In recent years, experimental studies of the effects of operational parameters on the cake structure and residual pressure drop in pulse-jet baghouse systems (for example, studies comparing factors such as humidity, pulse pressure, and the presence of a venturi) confirm that the regeneration geometry and pulse mode are factors that require "fine tuning" but sharply determine efficiency and energy consumption. Therefore, in world practice, the main vector for improving baghouse systems is to increase the thermomechanical stability of the filtering medium, improve cake control, and use design solutions that evenly distribute regeneration.

The selection of filter materials in high-temperature and abrasive environments has developed into a separate scientific area. Although polymer fiber fabrics (e.g. PPS, P84, etc.) are widely used in industry, in some hot and high-spark areas, mineral fibers or mineral-layered composites may be preferable. In industrial practice, the concept of filter bags using basalt layers (scrim) to increase spark resistance is also found; this approach shows that basalt fibers can be not only "heat-resistant", but also a structural component that reduces operational risks (sparks, punctures, tears). It is this approach that is important for the content of 2.2: when forming a basalt fiber filter layer (needle-punched nonwoven structure, interlayer reinforcement, gradient architecture), along with the thermal stability of the material, resistance to regeneration cycles, resource preservation under the influence of abrasion and ensuring "non-sticking" cake separation are considered as primary criteria. In this regard, the literature notes that the distinction between cake filtration and "fabric filtration" directly affects the rate of increase in pressure loss; that is, in practice, in most cases, the main "active medium" of filtration is not the fabric itself, but the cake, and the function of the filter layer structure is to control the stable formation and regeneration of the cake. Based on this logic, multi-layer (prefilter + main layer + support/protective layer) gradient structures are a concept widely used in world practice, which, by initially retaining large fractions, slows down the rapid clogging of the main layer and "smoothes" the dynamics of ΔP; this is associated with reducing energy consumption and extending the service life.

In the local context, there are also informational and scientific and practical articles in Uzbekistan on basalt fiber and its industrial applications: reviews on the chemical composition, production technology and areas of application of basalt fiber serve to substantiate basalt fiber as a promising material for high-temperature environments. Local publications on the environmental aspects of the cement industry and the problems of cleaning dust-gas flows also analyze dust and harmful gas cleaning devices, their efficiency and environmental consequences; these sources indicate that there is a practical problem in Uzbekistan and a high need for modern filtration approaches to solve it. However, when summarizing the literature, it is clear that local works tend to cover more "problems and general solutions", while in world experience there is a strong tendency to deeply optimize the structure of the filtering layer (nonwoven/needling, interlayer bonding, modification) in combination with regeneration mechanisms. Therefore, the scientific novelty and practical value of the article on the formation of a filtering layer based on basalt fiber is aimed at closing this gap: considering the basalt fiber

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filtering medium not as a "material", but as an integration of "material-structure-regeneration", substantiating a technological approach that serves to maintain ΔP stability under conditions of dispersion and abrasiveness of cement dust, avoid resource loss during regeneration cycles, and achieve low emission levels consistent with the global BAT logic [6-10].

Results and Discussion

The objective of this study is to scientifically substantiate the technology for forming a **basalt fiber–based filtering layer** intended for filtration of high-temperature, abrasive, and finely dispersed cement dust–gas flows. In accordance with this objective, the discussion focuses on treating the filtering medium not as an isolated material, but as a **controlled technological system integrating material properties, structural organization, and regeneration behavior**. Accordingly, the results are not presented as experimental measurements, but as a **calculation-based and theory-driven technological framework** that links structural parameters of the filtering layer to filtration performance, pressure-drop stability, and regeneration efficiency.

Filtration performance is conventionally evaluated using the particle collection efficiency η\etaη, defined as

$$\eta = \left(1 - \frac{C_{\text{out}}}{C_{\text{in}}}\right) \cdot 100\%,$$

where Cin and Cout represent the dust concentrations at the inlet and outlet of the filter, respectively. However, industrial experience shows that long-term operability and energy efficiency of baghouse systems are more strongly constrained by the evolution of the pressure drop P rather than by instantaneous collection efficiency. The pressure drop across a fabric filter can be expressed in simplified form using a Darcy-type relationship:

$$\Delta P = \mu\, v_f (R_m + R_c),$$

where μ is the dynamic viscosity of the gas, vf is the filtration velocity, Rm is the resistance of the clean filtering medium, and Rc is the resistance of the dust cake. This expression highlights that, although the thermal stability of basalt fibers ensures stability of Rm at elevated temperatures, the dominant contribution to pressure-drop growth in real operation arises from the dust-cake resistance Rc. Consequently, the key technological task addressed in this work is the structural control of dust-cake formation and removal.

To address this task, a multi-layer (gradient) filtering architecture is justified. In such a configuration, a prefilter layer located on the gas-inlet side captures coarse particles and redistributes the dust load, while the main basalt fiber layer ensures fine-particle retention. A support/protection layer enhances mechanical integrity during regeneration cycles. This structural approach reduces the rate of cake densification on the main layer, delays the critical growth of Rc, and contributes to stabilization of ΔP [11-15].

The selection of a needle-punched nonwoven structure for the basalt fiber filtering layer is analyzed from the standpoint of regeneration durability. During pulse-jet cleaning, the filtering medium is subjected to short-duration reverse-flow impulses and cyclic mechanical stresses. If fiber bonding within the structure is insufficient, repeated loading may cause fiber breakage, surface fuzzing, or progressive micro-damage. This behavior can be conceptually expressed by

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relating the probability of structural damage D to the ratio between impulse-induced stress σ imp and fiber-bond strength σ_bond:

$$D \propto \frac{\sigma_{\text{imp}}}{\sigma_{\text{bond}}}.$$

Needle punching increases σ_bond by mechanically interlocking fibers, thereby reducing D and improving resistance to repeated regeneration cycles. At the same time, excessive needling density may increase medium resistance R_m, illustrating the need to optimize structural parameters to achieve a balance between collection efficiency, pressure drop, and mechanical durability.

Table 1. Influence of structural and technological parameters on filtration performance

Parameter	Symbol	Change trend	Effect on η	Effect on ΔP	Technological interpretation
Fiber diameter	d_f	↓	↑ (improved fine-particle capture)	↑	Compensated by gradient structure
Layer thickness	L	↑	↑	↑	Prefer load redistribution via prefilter
Porosity	ε	↑	↓	↓	Balanced by multilayer architecture
Areal density	G (g/m²)	↑	↑	↑	Optimal G ensures efficiency–energy compromise
Needling density	n_p	↑	↑ (structural stability)	±	Excessive densification should be avoided
Hydrophobic treatment	—	on/off	↑ (in humid conditions)	↓ or ±	Reduces dust cementation
Antistatic treatment	—	on/off	↑	↓ or ±	Limits electrostatic adhesion
Thermal stabilization	—	on/off	stable	stable	Improves resistance to thermal cycling

The technological objectives are further examined by considering the dust loading on the filter surface. For an inlet dust concentration C_in and gas flow rate Q, the mass flow rate of dust entering the filter is:

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$$\dot{m} = C_{\text{in}} Q.$$

When distributed over the total filter area A, the dust loading per unit area becomes:

$$\dot{m}_A = \frac{\dot{m}}{A} = \frac{C_{\text{in}} Q}{A} = C_{\text{in}} v_f,$$

since $A = Q / v_f$, This relationship demonstrates that increasing filtration velocity directly increases the rate of dust-cake formation. Therefore, the structural design of the filtering layer must ensure effective cake management under elevated v_f and C_{in}, reinforcing the necessity of gradient structures and surface modifications.

The effectiveness of pulse-jet regeneration can be conceptually characterized by a dust-cake removal coefficient:

$$\varphi = \frac{m_{\text{removed}}}{m_{\text{deposited}}},$$

where m_deposited is the dust mass accumulated during filtration and m_removed is the mass detached during regeneration. Values of φ approaching unity indicate efficient cleaning, slower growth of R_c, and more stable pressure drop. The proposed technological measures—needle-punched structure, gradient layering, and hydrophobic or antistatic treatments—are directed toward increasing φ by facilitating cake detachment and preventing excessive adhesion.

Table 2. Influence of filtration velocity on dust loading and technological requirements

Scenario	C_in (g/m³)	v_f (m/min)	ṁ_A = C_in · v_f (g/(m²·min))	Technological implication
1	2.0	0.8	1.6	Moderate cake growth; basic gradient structure sufficient
2	2.0	1.0	2.0	Stable regeneration required; optimized needling and density
3	2.0	1.2	2.4	Rapid cake growth; hydrophobic/antistatic treatment recommended

Overall, the analysis confirms that the effectiveness of basalt fiber–based filtering media in high-temperature cement dust applications depends not solely on thermal resistance, but on structural engineering of the filtering layer. Within the pressure-drop framework ΔP = μ·v_f·(R_m + R_c), the proposed measures primarily act to control the evolution of R_c, thereby stabilizing pressure loss and extending service life. The present work delivers a coherent, calculation-based technological platform defining the key parameters to be verified in subsequent laboratory and industrial trials, including pressure-drop evolution ΔP(t), collection efficiency η, regeneration efficiency φ, and operational durability under real cement-plant conditions [16-19].

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Figure 1. Basalt Fiber–Based Heat-Resistant Filtration System for Cement Dust Control

Conclusion

This study substantiates the technological and methodological foundations for forming a **heat-resistant basalt fiber–based filtering layer** intended for use in high-temperature and abrasive cement dust–gas environments. Relying on global industrial experience and theoretical analysis rather than experimental measurements, the work demonstrates that filtration performance in such conditions is governed not only by the choice of filter material, but by the integrated interaction between **material properties, structural configuration, and regeneration dynamics**.

The selection of **needle-punched nonwoven basalt fiber structures** is justified by their enhanced mechanical integrity and elasticity under repeated pulse-jet loading. From a mechanistic perspective, stronger fiber bonding increases resistance to regeneration-induced stresses, thereby reducing the probability of structural damage and fiber degradation. Additional surface modifications, such as hydrophobic or antistatic treatments, are shown to

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be conceptually effective in mitigating moisture-induced cementation and electrostatic adhesion of dust particles, further improving cake release efficiency and operational stability. Overall, the results indicate that basalt fiber–based gradient filtering media provide a scientifically sound and technologically viable solution for high-temperature cement dust filtration. The principal outcome of this work is the formulation of a **design-oriented, calculation-based technological platform** that links filtration efficiency, pressure drop behavior, and regeneration performance to controllable structural parameters of the filter medium. This platform creates a reliable basis for subsequent laboratory and industrial trials, where quantitative evaluation of collection efficiency, pressure drop evolution, regeneration efficiency, and service life can be performed to finalize optimal design parameters for practical implementation.

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