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Theoretical Foundations of The Aerodynamics of An Improved Bag Filter Device Utilising Composite Filter Fabric

Mullajonova Maftuna Malikjon qizi

Assistant, Fergana State Technical University, Fergana, Republic of Uzbekistan

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Abstract: This article examines the theoretical justification of the aerodynamic resistance of an advanced bag filter apparatus. The total pressure loss within the device is interpreted as the summation of losses occurring during the intake of the dust-laden gas stream, its longitudinal axial movement within the filter sleeve, the radial filtration process through the composite filter medium, and local resistances encountered within the housing and the purified gas discharge zones. The microstructural characteristics of the filter fabric, based on a combination of polyester, glass fibre, and basalt fibre—including parameters such as thickness, specific contact surface area, the fraction of open zones, and the degree of dust cake formation—are considered the primary determining factors of the radial resistance coefficient. Consequently, an analytical approach is proposed that enables the evaluation of the total aerodynamic resistance while accounting for the actual microstructural state of the composite filter fabric.

Keywords: Bag filter, Aerodynamic resistance, Pressure loss, Radial filtration, Composite filter fabric, Basalt fibre.

INTRODUCTION:

In the contemporary landscape of industrial environmental protection, the purification of dust-laden gases stands as a critical challenge for ensuring atmospheric sustainability and meeting stringent emission standards [1, 2]. Bag filter units have emerged as the predominant technology in this domain, distinguished by their superior separation efficiency, particularly for capturing fine and ultra-fine particulate matter [3, 4]. Despite their widespread application, the operational stability and long-term performance of these systems are intrinsically linked to their aerodynamic characteristics [5]. An excessive increase in the total pressure drop within the filtration system not only leads to a substantial surge in energy consumption but also imposes significant constraints on the filtration velocity, thereby diminishing the overall operational lifespan of the filter media [6, 7].

The complex fluid dynamics within an advanced bag filter assembly necessitate a rigorous theoretical framework to accurately quantify the aerodynamic resistance across several functional zones [8]. According to established hydrodynamic principles, the total pressure loss is not a monolithic value but a complex summation of resistances occurring at various stages of the gas flow path: − The initial intake of the dust-laden gas stream, where sudden changes in flow direction and velocity generate local head losses [9]; − The axial movement of the gas along the internal length of the filter sleeve, governed by frictional forces and Reynolds number variations [10, 11]; − The radial filtration phase through the composite filter fabric, which represents the most critical zone where Darcy’s law and porous media mechanics are typically applied [12, 13]; − The secondary resistance caused by the progressive formation of the dust cake layer on the fabric surface [14]; − The final discharge of the purified gas through the housing and outlet manifolds, where additional local resistances are encountered [15].

Recent advancements in materials science have introduced hybrid filter media that combine the mechanical strength and thermal stability of polyester, glass fibre, and basalt fibre [16]. Such composite structures offer unique microstructural properties—including specific contact surface area, pore tortuosity, and varied packing densities—that significantly alter the radial resistance coefficients compared to conventional mono-component fabrics [17, 18].

The primary objective of this research is to provide a comprehensive theoretical justification for the aerodynamic resistance in an improved bag filter device (Figure 1). By synthesising the hydrodynamic interactions between the gas flow and the multi-component micro-structure of the filter media, this study aims to develop an enhanced analytical model. This approach integrates the specific impacts of fibre morphology and dust accumulation, serving as a robust foundation for the computational optimisation of filtration systems and providing a theoretical benchmark for future experimental validation.

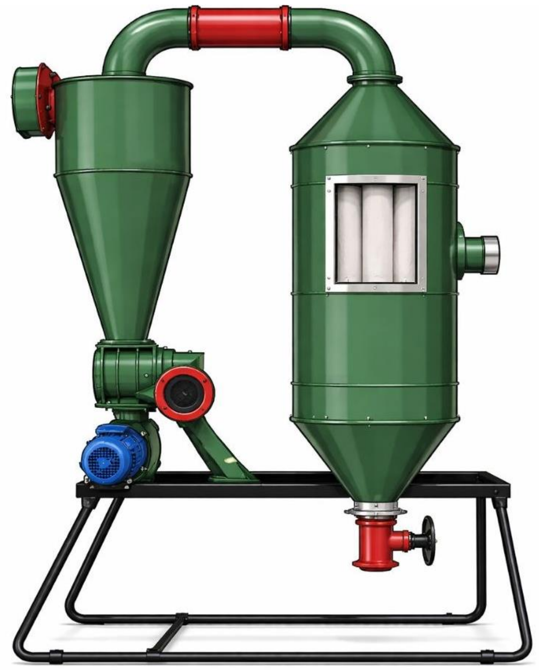

Figure 1. An improved bag filter device equipped with a filter fabric based on a combination of polyester, glass fiber, and basalt fiber.

METHODS

In an improved bag filter device, the total aerodynamic resistance is generated as a result of the movement of the dust-laden gas stream within the apparatus, changes in flow direction, the expansion or contraction of cross-sectional areas, friction within the filter sleeve, and the processes of passing through both the filter fabric and the accumulated dust cake. Consequently, it is scientifically and practically preferable to analyse the total pressure loss not as a single aggregate parameter, but by partitioning it according to the functional zones of the device.

In the enhanced bag filter design, aerodynamic resistance primarily develops in the following zones: the gas stream inlet, the movement of gas within the filter sleeve (bag), the passage through the filtration layer (the fabric and the dust cake), the clean gas collection zone within the device housing, and the exit zones of the apparatus. Each of these zones is subject to specific hydrodynamic principles. For instance:

− Local losses at the dust-laden gas inlet and outlet, as well as within the housing, are evaluated primarily based on the Bernoulli equation and the laws of local resistance coefficients;

– Flow resistance within the sleeve is assessed using the Darcy–Weisbach equation;

– The pressure drop during the passage through the filter fabric and the dust cake is evaluated according to Darcy's law for flow in porous media, and if high velocities are involved, by incorporating the Forchheimer correction.

Therefore, for the theoretical assessment of the total aerodynamic resistance of a bag filter unit, it is necessary to apply the appropriate physical laws and computational expressions for each specific zone. In this case, the equation for the total aerodynamic resistance of the bag filter, categorised by zones, can be expressed as follows, in Pa:

$$\Delta P_{um} = \Delta P_{kir} + \Delta P_{eng} + \Delta P_{kor} \qquad (1)$$

Where:

ΔP_{um} — is the total aerodynamic resistance of the apparatus, Pa; ΔP_{kir} — is the pressure loss in the inlet zone, Pa, Па; ΔP_{eng} — is the pressure loss within the sleeve and across the filter fabric layer, Pa; ΔP_{kor} — is the pressure loss within the device housing and the purified gas discharge zone, Pa.

The pressure loss in the inlet zone occurs as a result of the dust-laden gas entering the apparatus through the inlet pipe, changes in flow direction, expansion of the flow cross-section, or distribution via a diffuser. The losses in this zone are primarily characterised by local resistance. The pressure drop in this section is governed by the law of local resistance derived from the Bernoulli equation and can be determined according to the following formula, Pa:

$$\Delta P_{kir} = \zeta_{kir} \frac{\rho v_{kir}^2}{2} \qquad (2)$$

Where:

$\upsilon_{кир}$ — is the velocity of the dust-laden gas in the inlet pipe of the apparatus, m/s;

$\rho_{ch.g.}$ — is the density of the gas, kg/m^3;

ζ_{kir} — is the local resistance coefficient of the inlet zone, which depends on the shape of the pipe and the configuration of the diffuser distributing the dust-laden gas within the apparatus, and is determined according to the following general equation:

$$\zeta_{kir} = \zeta_{pat} + \zeta_{bur} + \zeta_{t.k.} + \zeta_{kol} + \zeta_{taq} \qquad (3)$$

Where:

ζ_{pat} — is the resistance coefficient of the dust-laden gas inlet pipe;

ζ_{bur} — is the resistance coefficient at the flow bend;

$\zeta_{t.k.}$ — is the resistance coefficient of the distribution chamber;

ζ_{kol}— is the resistance coefficient of the distributing manifold;

ζ_{taq}— is the resistance coefficient for the gas distribution into individual sleeves.

In general, the resistance coefficient of the inlet section for the gas flow into the bag filter can be expressed as follows:

$$\zeta_{kir} = \lambda_{k.q.} \frac{l_{k.q.}}{d_{k.q.}} + f\left(\theta \frac{R}{d_{k.q.}}\right) + \left(1 - \frac{F_{k.q.}}{F_k}\right)^2 + \lambda_{kol} \frac{l_{kol}}{d_{kol}} + \zeta_{k.m.} + \zeta_{taq} \qquad (4)$$

Where:

λ_0 — is the friction coefficient in the inlet pipe;

l_0 — is the length of the inlet pipe, m;

d_0 — is the diameter of the inlet pipe, m;

θ — is the bend angle, deg;

R — is the radius of the bend, m;

F_0 — is the cross-sectional area of the inlet pipe, m^2;

F_k — is the free cross-sectional area corresponding to the distribution chamber, m^2;

λ_k — is the friction coefficient within the distribution chamber;

l_k — is the length of the distribution section, m;

d_k — is the hydraulic diameter of the distribution section, m;

If the inlet pipe is a cylindrical duct, the pressure loss follows the Darcy–Weisbach law and is generally determined according to the following formula, Pa

$$\Delta P_{kir} = \left[\lambda_{k.q.} \frac{l_{k.q.}}{d_{k.q.}} + f\left(\theta \frac{R}{d_{k.q.}}\right) + \left(1 - \frac{F_{k.q.}}{F_k}\right)^2 + \lambda_{kol} \frac{l_{kol}}{d_{kol}} + \zeta_{k.m.} + \zeta_{taq} \right] \frac{\rho \upsilon_{kir}^2}{2} \quad (5)$$

In analyzing the aerodynamic resistance of a bag filter based on a combination of polyester, glass fibre, and basalt fibre, the movement of the gas stream must be considered across two interconnected stages. In the first stage, the dust-laden gas enters the filter sleeve and moves along its internal cavity. In the second stage, the gas undergoes radial filtration through the composite filter fabric, which serves as the sleeve wall. Consequently, interpreting the aerodynamic resistance within the filter sleeve solely as a loss resulting from friction along a cylindrical channel is insufficient. Here, the axial flow within the sleeve, radial suction through the filter wall, microstructure porosity, specific contact surface area, the geometry of open zones, and the formation rate of the dust cake layer exert a collective influence.

RESULTS

According to the results of microstructural studies conducted on the filter fabric, it was determined that in the mixed filter layer composed of basalt and glass fibers placed between polyester support layers, the specific contact surface area consistently increases as the fabric thickness increases (Figure 2). Specifically, at a thickness of 1 mm, the total contact surface area was 1.98 m2/m2; at 1.2mm, it reached 2.28m2/m2; and at 1.5 mm, it amounted to 2.66 m2/m2. This phenomenon is explained by the mutual compaction of fibres, the strengthening of bonding, and the increase in the active internal surface area. Simultaneously, an increase in the complexity of the open zone geometry and a narrowing of the air passage channels are observed. These results indicate that several factors act in combination during the formation of aerodynamic resistance within the filter sleeve.

Figure 2. Filter fabric based on a combination of polyester, glass fiber and basalt fiber

Firstly, the gas flow within the sleeve loses pressure as a result of friction against the sleeve walls. Secondly, the continuous radial exit of gas through the filter wall alters the velocity field of the flow along its length. Thirdly, as the specific contact surface area increases, the free passage channels between the fibres are reduced, leading to a decrease in radial permeability and an increase in resistance to the passage of gas through the fabric. Fourthly, in layers with a high contact surface area, the intensity of dust particle entrapment is enhanced, causing the dust cake to form more rapidly. This, in turn, leads to a progressive increase in resistance over time.

From this perspective, it is appropriate to consider the total aerodynamic loss within the filter sleeve as the sum of the friction loss arising from the flow movement along the sleeve, the loss associated with radial filtration through the filter wall, and the local loss generated as a result of flow redistribution; this is determined according to the following formula, Pa:

$$\Delta P_{eng} = \Delta P_{e.r.u.} + \Delta P_{rad} \quad (6)$$

Where:

$\Delta P_{e.r.u.}$ — is the pressure loss of the dust-laden air flow due to friction during its movement along the sleeve axis, Pa;

ΔP_{rad} — is the pressure loss occurring due to radial filtration through the filter wall, Pa.

$\Delta P_{e.r.u.}$ represents the pressure loss caused by friction with the inner wall as the dust-laden gas moves along the axis inside the filter sleeve. Its value depends on the operating length of the sleeve, the equivalent diameter, the gas density, the average velocity within the sleeve, and the friction coefficient, and is primarily evaluated based on the Darcy–Weisbach law. This expression is considered significantly more accurate from an engineering perspective for determining the resistance inside the filter sleeve. In that case, the axial pressure loss along the sleeve can be generally written according to the Darcy–Weisbach equation as follows, Pa,

$$\Delta P_{e.r.u.} = \lambda \frac{L_{eng}}{d_{eng}} \frac{\rho \upsilon_{e.k.t}^2}{2} \quad (7)$$

Where:

λ — is the friction coefficient of the sleeve's inner surface;;

L_{eng} — is the operating length of the sleeve, m;

d_{eng} — is the equivalent diameter of the sleeve, M;

$\upsilon_{e.k.t.}$ — is the velocity of the dust-laden gas flow entering the sleeve, .m/s.

However, in bag filter conditions, υe.k.t is not constant, as it decreases along the length of the sleeve due to the gas exiting through the sleeve walls. Therefore, in real conditions, the pressure loss due to friction inside the filter sleeve differs from the classic value for a cylindrical channel and should be evaluated in an effective or integral form.

ΔP_{rad} represents the pressure loss occurring during the radial passage of gas through the composite fabric serving as the filter sleeve wall. It depends on the thickness of the filter fabric, the specific contact surface area, the pore structure, the filtration velocity, and the degree of dust cake formation; it is considered the primary aerodynamic resistance component of the filter layer and is expressed by the following formula, Pa:

$$\Delta P_{rad} = \zeta_{rad} \frac{\rho \upsilon_{rad}^2}{2} \quad (8)$$

Where:

ζ_{rad} is the equivalent resistance coefficient for radial filtration through the filter sleeve wall; υ_{rad} — is the filtration velocity in the radial direction through the filter fabric, m/s.

According to equation (8), the radial pressure loss depends on the equivalent resistance coefficient, the gas density, and the square of the filtration velocity. However, ζ_{rad} is not a constant value; it is treated as a variable parameter depending on the structure of the filter fabric and its condition during the operation process.

From a physical perspective, an increase in the thickness of the filter fabric extends the path the gas must travel within the fibrous medium, consequently increasing resistance. An increase in the specific contact surface area expands the interaction area between the fibres and the gas flow, which, along with increasing the entrapment intensity of dust particles, reduces the free passage channels for the gas. A decrease in the fraction of open zones leads to a reduction in permeability within the filter medium. The increase in the mass of the dust cake partially blocks the pores, forming additional resistance within the filter medium. Therefore, taking these factors into account, the radial resistance coefficient can be expressed as follows, Pa:

$$\zeta_{rad} = \zeta_{r0}\left(1+a_{\delta}\delta_f\right)\left(1+a_s S_{um}\right)\left(1+a_m m_{ch}\right)\left(1+P_{o.u.}\right)^n \quad (9)$$

Where:

ζ_{r0} is the base radial resistance coefficient;

a_{δ} is the coefficient of influence of the fabric thickness;

a_s is the coefficient of influence of the specific contact surface area;

a_m is the coefficient of influence of the dust cake mass;

$P_{o.u.}$ is the fraction of open zones, m^2;

n is the index representing the degree of influence of the open zone fraction on resistance.

of the open zone fraction on resistance.

This expression implies that as the filter fabric becomes thicker, the specific contact surface area increases, and the dust cake accumulates, the radial resistance coefficient also increases. Conversely, an increase in the fraction of open zones facilitates radial passage and reduces the resistance coefficient. Thus, the pressure loss resulting from radial filtration takes the following form, Pa:

$$\Delta P_{rad} = \left[\zeta_{r0}\left(1+a_{\delta}\delta_f\right)\left(1+a_s S_{um}\right)\left(1+a_m m_{ch}\right)\left(1+P_{o.u.}\right)^n\right]\frac{\rho\upsilon_{rad}^2}{2} \quad (10)$$

Equation (10) allows for the simultaneous consideration of the actual microstructural state of the filter fabric, including its thickness, specific contact surface area, the fraction of open zones, and the effect of dust cake accumulation. As a result, a convenient analytical expression is obtained to theoretically justify the aerodynamic resistance generated by the radial filtration process through the filter sleeve wall and to compare it with experimental data.

Based on the results of the microstructural analysis conducted, the empirical variation of the specific contact surface area as a function of fabric thickness can also be taken into account. According to the experimental results, within the interval of 1.0–1.5 mm, the specific contact surface area is expressed through the following linear relationship:

$$S_{um} = 1.36\delta_f + 0.63 \quad (11)$$

Where:

δ_f is the fabric thickness, mm.

By substituting this relationship into the expression for the radial resistance coefficient, ζrad can also be expressed in terms of thickness;

$$\zeta_{rad} = \zeta_{r0}\left(1+a_{\delta}\delta_f\right)\left(1+a_s\left(1.36\delta_f+0.63\right)\right)\left(1+a_m m_{ch}\right)\left(1+P_{o.u.}\right)^n \quad (12)$$

The formula for radial pressure loss then takes the following form, Pa:

$$\Delta P_{rad} = \left[\zeta_{r0}\left(1+a_{\delta}\delta_f\right)\left(1+a_s\left(1.36\delta_f+0.63\right)\right)\left(1+a_m m_{ch}\right)\left(1+P_{o.u.}\right)^n\right]\frac{\rho\upsilon_{rad}^2}{2} \quad (13)$$

The pressure loss resulting from radial filtration through the filter wall depends on the microstructure of the composite fabric, and its primary defining parameters are the thickness of the filter layer, the specific contact surface area, the fraction of open zones, the filtration velocity, the density and viscosity of the gas, and the mass of dust accumulated on the filter surface. For this reason, the radial resistance coefficient is expressed in a semi-empirical form by introducing correction factors to the base value. This approach allows for the consideration of the actual aerodynamic properties of the composite filter fabric based on polyester, glass fibre, and basalt fibre.

By expressing equation (5) through equations (7) and (13), the formula for the total aerodynamic resistance of the filter sleeve to the dust-laden gas flow takes the following form, Pa:

$$\Delta P_{eng} = \lambda \frac{L_{eng}}{d_{eng}} \frac{\rho \upsilon_{e.k.t}^2}{2} + \\ + \left[\zeta_{r0} \left(1 + a_\delta \delta_f\right) \left(1 + a_s \left(1.36\delta_f + 0.63\right)\right) \left(1 + a_m m_{ch}\right) \left(1 + P_{o.u.}\right)^n \right] \frac{\rho \upsilon_{rad}^2}{2} \tag{14}$$

The pressure loss generated during the movement of the cleaned gas exiting the filter sleeves within the casing and its direction towards the outlet pipe also plays a significant role in the overall aerodynamic resistance of the apparatus. This loss is denoted as ΔPkor.

Physically, ΔPkor occurs during the merging of cleaned gas streams within the casing, their redistribution, change of direction, and transition into the outlet pipe. In this case, a certain portion of the flow loses energy under the influence of local resistances, resulting in a pressure drop.

Since this loss is associated with local geometric changes rather than friction along the length, it is determined based on the law of local hydraulic resistances, Pa:

$$\Delta P_{kor} = \zeta_{kor} \frac{\rho \upsilon_{kor}^2}{2} \tag{15}$$

Where:

ζ_{kor} is the local resistance coefficient for the casing and the outlet zone; υ_{kor} is the characteristic gas velocity in the casing or the outlet pipe, m/s;

The value of ΔP_{kor} primarily depends on the geometric dimensions of the casing, the diameter of the outlet pipe, the flow redistribution conditions, and the gas velocity and density. A reduction in the cross-section of the outlet pipe or an uneven distribution of the flow increases the local resistance, subsequently leading to an increase in pressure loss.

Thus, ΔP_{kor} represents the local aerodynamic loss occurring during the merging, redistribution, and transition of the flow into the outlet pipe within the apparatus casing and the cleaned gas exit zone; it must be taken into account when determining the total aerodynamic resistance of the apparatus.

DISCUSSION

Although equations (14) and (15) are theoretically complete, their direct practical calculation presents certain complexities. This is due to the following reasons:

- Firstly, the gas velocity within the sleeve is not constant along its length, as the gas exits radially through the sleeve walls;

- Secondly, the specific contact surface area of the filter fabric, the fraction of open zones, and the degree of dust cake formation are variable parameters during the operation process;

- Thirdly, the radial resistance coefficient is not constant but depends on the fabric thickness, specific contact surface area, fraction of open zones, and the mass of the dust cake;

- Fourthly, the local and casing resistances are also interconnected due to the redistribution of flow and the change in characteristic velocity.

For these reasons, it is difficult to determine the total aerodynamic resistance in a strictly analytical closed form; the problem essentially transforms into a coupled hydrodynamic system with variable coefficients.

Based on the above, to express the total aerodynamic resistance in a holistic form, the x coordinate is introduced along the filter sleeve, and the elementary change in pressure is written as the sum of the following structural influences, Pa:

$$\Delta P_{um} = \zeta_{kir} \frac{\rho v_{kir}^2}{2} + \lambda \frac{L_{eng}}{d_{eng}} \frac{\rho \overline{v}_x^2}{2} + \zeta_{rad}^* \frac{\rho \overline{v}_{rad}^2}{2} + \zeta_{mah}^* \frac{\rho \overline{v}_x^2}{2} + \zeta_{kor} \frac{\rho v_{kor}^2}{2} \tag{16}$$

CONCLUSION

The theoretical analysis conducted showed that the total aerodynamic resistance of the improved bag filter apparatus should be considered as the sum of the local losses in the inlet zone, the axial movement within the sleeve, the radial filtration through the composite filter fabric, and the casing-outlet zone. Such an approach allows for the explanation of the pressure loss formation mechanisms across specific zones of the apparatus.

According to the research results, the thickness of the filter fabric, the specific contact surface area, the fraction of open zones, and the mass of the dust cake are considered the primary factors determining the radial resistance coefficient. An increase in the specific contact surface area and a decrease in the fraction of open zones enhance the resistance to gas passage through the filter wall, while the formation of the dust cake further complicates this process over time. Therefore, applying semi-empirical expressions for the composite filter fabric is considered the optimal approach for theoretical assessment.

At the same time, it was established that expressing the total aerodynamic resistance in a strictly analytical closed form is difficult due to the variability of the gas velocity along the length of the sleeve, the non-constant nature of the radial resistance coefficient, and the interconnectedness of local resistances. Consequently, the proposed theoretical approach serves as an important scientific basis for analyzing the hydrodynamic regimes of the improved bag filter apparatus, optimizing its design parameters, and linking it with experimental studies.

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