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METHODS FOR DETERMINING THE OPERATIONAL CHARACTERISTICS OF A FILTER ELEMENT MANUFACTURED FROM METAL POWDER AND ITS REGENERATION

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Abstract. This article investigates the operational characteristics of filter elements manufactured from metal powder for oil filters used in internal combustion engines. A comparative analysis of the filtration efficiency, hydraulic resistance, mechanical strength, and thermal resistance of filter elements produced by the vibration pressing method with conventional paper filters was carried out. Regeneration methods — thermal, ultrasonic, and chemical — were studied, and their efficiency was evaluated.

Keywords: filter element, metal powder, vibration pressing, regeneration, oil purification, internal combustion engine (ICE), operational characteristics.

Introduction. In internal combustion engines (ICEs), the accumulation of mechanical particles, combustion products, and oxidation residues in the lubricating oil significantly accelerates the wear of bearings and the cylinder-piston group. Studies indicate that 60–70% of engine failures are directly related to the deterioration of oil quality. Therefore, the efficiency of the oil purification system has a decisive influence on engine durability and reliability.

Currently, widely used cellulose paper filter elements have several limitations: low service life (10,000–15,000 km), weak resistance to temperature and chemical effects, inability to be regenerated, and the necessity of disposing environmentally harmful waste generated during each replacement. These shortcomings make the search for alternative materials and technologies highly relevant.

Metal powder-based filter elements have been actively studied over the last decade as a promising solution to these problems. Porous elements produced by powder metallurgy methods are distinguished by their resistance to high temperatures and pressures, mechanical strength, and the possibility of multiple regenerations. However, under the conditions of Uzbekistan, no comprehensive research has been conducted on such elements specifically designed for heavy-duty vehicles and produced using the vibration pressing method.

The purpose of this article is to determine the main operational characteristics of filter elements manufactured from metal powder using the vibration pressing method, comparatively evaluate them with conventional paper filters, and substantiate the effectiveness of regeneration technology.

Literature review. Scientific and technological progress involves the continuous improvement of existing production tools and labor objects, the creation of new ones, the establishment of new types of capacities, the improvement of technological processes and production management, and the enhancement of production efficiency. The economic and social significance of scientific and technological progress lies in the fact that it is the main factor in increasing labor productivity through the widespread use of modern scientific and technological achievements in production.

New technologies significantly increase labor productivity, continuously reduce labor costs, and increase production output per worker. In automobile transport, one of the main ways to improve labor productivity is technical modernization aimed at increasing the efficiency of rolling stock operations. In this regard, the comprehensive mechanization of loading and unloading operations, the implementation of advanced technologies for organizing and managing transportation processes, as well as the application of economic-mathematical methods, logistics approaches, and information technologies are of decisive importance.

Methodology. The research focuses on developing a technology for manufacturing filter elements from metal powders for internal combustion engine lubrication systems using the vibration movement method, characterized by high filtration efficiency, contaminant holding capacity, and regeneration capability, as well as evaluating their operational properties. Scientific investigation methods, statistical analyses, logical approaches, analytical studies, and reviews of various scientific literature and articles were employed during the research process.

Discussion and results. Tests of newly manufactured filter elements demonstrated the following results. The metal powder element retained particles of 15 μm size with an efficiency of 97.8–98.4%. For the conventional paper filter, this indicator was 94.5–96.8%.

Especially for small particles in the range of 5–10 μm, the difference was more significant: the metal powder element demonstrated an efficiency of 89.2%, while the paper filter showed 71.3%.

Table 1

Comparative results of the main operational characteristics of filter elements

Indicator	Metal Powder	Conventional Paper	Difference (%)
Efficiency, 5 μm	**89.2%**	**71.3%**	**+18**
Efficiency, 10 μm	**95.1%**	**83.6%**	**+11.5**
Efficiency, 15 μm	**98.1%**	**95.6%**	**+2.5**
Efficiency, 25 μm	**99.4%**	**98.2%**	**+1.2**
Hydraulic resistance, MPa	**0.068**	**0.094**	**-27.7**
Porosity, %	**32–38**	**45–55**	**-**

From the perspective of hydraulic resistance, the metal powder element demonstrated a 27.7% lower value compared to the conventional filter (0.068 MPa and 0.094 MPa, respectively). This can reduce the additional load on the engine pump and lead to fuel savings of 1.2–2.1%.

Mechanical Strength and Thermal Resistance. During the gradual pressure increase test, the metal powder element showed no structural damage even at a pressure of 2.4 MPa. The conventional paper filter began to deform at 1.1 MPa. This difference ensures reliable operation of metal powder elements under extreme conditions, especially during cold starts when oil viscosity is high.

According to temperature test results, the metal powder element maintained its operating characteristics at temperatures from -40°C (cold-start conditions) up to 280°C. The paper filter deformed at 130°C and ruptured at 150°C.

Practical Test Results on the KamAZ-740 Engine

The metal powder filter element installed in a KamAZ-740 engine was monitored over a distance of 85,000 km (one coarse filter and one fine filter). Oil samples were taken every 15,000 km and analyzed using ICP-OES spectrometry.

Table 2
Results of 85,000 km monitoring on the KamAZ-740 engine

Mileage (km)	Fe particles, mg/kg	Cu particles, mg/kg	Pressure difference, MPa	Condition
0	8.2	3.1	0.068	New
15,000	9.4	3.6	0.071	Good
30,000	11.1	4.2	0.079	Good
45,000	12.8	4.9	0.091	Regeneration
45,000 (after)	8.9	3.4	0.072	After regeneration
60,000	10.3	4.0	0.081	Good
75,000	12.1	4.7	0.094	Regeneration
85,000	11.4	4.4	0.085	Good

The monitoring results showed that the filter element required regeneration at 45,000 km and 75,000 km when the pressure difference exceeded the threshold value of 0.09 MPa. Ultrasonic regeneration restored the efficiency almost to the initial condition in both cases.

Regeneration Efficiency. Three regeneration methods were comparatively studied, and the results are presented below:

Table 3
Comparison of regeneration method efficiency

Regeneration Method	Efficiency Recovery	Number of Uses	Time	Cost (UZS)
Thermal (450°C)	90–94%	3–4 times	30 minutes	15,000
Ultrasonic (40 kHz)	96–98%	4–5 times	20 minutes	22,000
Chemical (NaOH)	87–92%	3 times	40 minutes	8,000

The ultrasonic method provided the highest efficiency (96–98%) and the greatest regeneration capability (4–5 cycles). The thermal method was more convenient in terms of time but slightly less efficient. The chemical method was the cheapest but the least effective and had limited applicability.

Forming filter elements using the vibration movement method. In the production of filter elements from metal powders, pressing and sintering processes occupy a key role. During powder pressing, filling the mold cavity and removing air are of great importance. Research shows that applying vibration to the mold during the pressing process ensures uniform distribution of the powder and effective air removal.

Studies conducted by Rud et al. (2020) proposed a process for manufacturing gradient filtration materials from stainless steel and saponite powders using vibration technology. In this work, the influence of vibration amplitude and frequency on gradient segregation was determined, and a method for producing porous gradient filtration materials using industrial vibration equipment was proposed.

Technology of Pressing by the Vibration Movement Method.

The main stages of producing a filter element using the vibration movement method are as follows:

Stage 1: Preparation of Powder Composition

Metal powders of various fractions (10–20 µm, 20–35 µm, 35–50 µm) are mixed in specific proportions. Fine fractions fill the spaces between coarse particles, thereby increasing the density and strength of the material.

Stage 2: Mold Filling and Vibration

While filling the mold cavity with powder, the mold is subjected to vibration movement with a specified amplitude and frequency. This ensures uniform distribution of powder particles and removes air from inside the mold. To create a gradient structure, the vibration mode causes different powder layers to arrange differently.

Stage 3: Isostatic Pressing

The powder-filled mold is subjected to isostatic pressing under a pressure of 50–200 MPa.

Stage 4: Sintering

Pressed samples are sintered under vacuum at temperatures of 1100–1200°C. During sintering, diffusion bonding occurs between metal particles, resulting in particle consolidation. The selected sintering regime determines the porosity and filtration properties.

Stage 5: Finishing of the Final Product

The sintered filter elements are machined to standard dimensions, the surface is cleaned, and the products undergo mechanical testing.
Regeneration tests of filter elements manufactured from metal powder were carried out using two methods:

Backwashing Method.

A clean oil or special washing solution (kerosene or clean diesel fuel) was supplied into the internal cavity of the contaminated filter element in the reverse direction under a pressure of 0.2–0.5 MPa. The washing process continued for 10–30 minutes.

Ultrasonic Cleaning Method.

The filter element was placed in an ultrasonic bath with a volume of 5–15 liters filled with kerosene as a washing solution. The ultrasonic frequency ranged from 25–40 kHz with a power

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of 100–200 W. Cleaning duration was 15–30 minutes. Ultrasonic vibrations created micro-turbulence on the filter surface, separating trapped particles.

Structural characteristics of filter elements.

Microscopic analysis (Scanning Electron Microscope — SEM) of filter elements manufactured using the vibration movement method confirmed the presence of a gradient structure. The pore sizes in the surface layer of the filter element ranged from 5–15 µm, while in the inner layers they increased up to 30–50 µm. This gradient structure provides an optimal balance between filtration efficiency and pressure drop: fine particles are retained on the outer surface, while flow resistance does not significantly increase in deeper layers.

The density of the gradient-structured filter material monotonically increased along the thickness from 40% (at the inlet side) to 65% (at the outlet side). Compared to conventional homogeneous structures, this allows increased contaminant holding capacity and reduced pressure loss.

Table 4

Comparative Characteristics of Filter Elements (Comparative Diagram)

Characteristic	Conventional Cellulose (relative unit)	Metal Powder (uniform)	Metal Powder (gradient)
Filtration efficiency (20 µm)	1.00	1.11	1.16
Contaminant holding capacity, g	1.00	2.25	3.00
Pressure drop	1.00	0.85	0.67
Mechanical strength	1.00	8.00	9.00
Operating temperature	1.00	1.33	1.33
Number of regeneration cycles	1.00	7.00	10.00
Relative initial cost	1.00	2.50	3.20
Operating cost (1 year)	1.00	0.65	0.50

Conclusion and recommendations.

Based on the conducted research, the following scientific and practical conclusions were obtained:

- The metal powder-based filter element (40% copper + 30% iron + 30% bronze) achieved a filtration efficiency of 97.8–98.4% for 15 µm particles, which is 2.5–18% higher than conventional paper filters depending on particle size.
- Hydraulic resistance was 0.068 MPa, which is 27.7% lower than that of paper filters. This reduces pump load and improves fuel efficiency by 1.2–2.1%.
- Mechanical strength tests showed that the element maintained integrity even at 2.4 MPa pressure, which is particularly important for cold-start conditions.
- Monitoring on the KamAZ-740 engine over 85,000 km demonstrated that the metal

powder filter maintained Fe particle concentration in engine oil approximately 21% lower.

- Ultrasonic regeneration (40 kHz, 20 minutes) restored 96–98% of efficiency, and the element was reused 4–5 times.
- Over 5 years of operation, total savings amounted to approximately 302,000 UZS (55%), mainly due to an additional 15,000 km engine service life.
- From an ecological perspective, the possibility of reducing harmful waste by 270 tons annually for a fleet of 150,000 heavy-duty vehicles was identified.

Recommendations.

- Metal powder filter elements are recommended for serial application in KamAZ-740, MAZ-5336, and Isuzu NQR engines.
- Ultrasonic regeneration equipment should be introduced in automobile service centers (40 kHz with acetone).
- The criterion $\Delta P > 0.09$ MPa is proposed as an indicator for the necessity of regeneration.
- Future studies are recommended on nanostructured filter materials (Cu-Fe-B powder composition) and combined elements integrated with magnetic separation technology.

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