Efficiency of using porous network material as a filter material in shutter filters

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Abstract. The problem of environmental protection is one of the most pressing at present. Internal combustion engines (ICE) play a large role in environmental pollution. In large cities, they are the main sources of toxic substances emitted into the atmosphere. Harmful emissions of automotive engines cause serious diseases in people and farm animals, reduce crop yields (up to 25%) and reduce the quality of crops (potatoes, corn, grains, etc.), especially in the roadside highways. To reduce emissions of particulate matter, a particulate filter has been developed, in which the porous mesh material P300 and P685, one-sided twill mesh, is used as the filter material. Tests of the developed particulate filter show high efficiency of its work. The efficiency of cleaning from soot ($\eta_C$) during the diesel engine operation on the external speed characteristic for the C685 grid is 90÷94%, for the P300 grid of three layers – 83÷92%, for the P300 grid of two layers – 71÷82%.

1. Introduction

Environmental pollution is one of the most pressing problems facing humanity at the present time. Internal combustion engines play an important role in environmental pollution. Harmful emissions from engines cause serious diseases in people and farm animals, reduce yields and reduce the quality of crops. Therefore, diesel engines are becoming more common in transport. This is due to the fact that diesel engines have better fuel efficiency compared to gasoline engines and, as a rule, less toxic emissions of exhaust gases (EG). However, they do not always meet the stringent requirements for exhaust emissions. Therefore, along with the improvement of the economic performance of diesel engines, reducing their toxicity is a major task. [1-3]

Exhaust gases from diesel engines are a complex multicomponent mixture of gases and dispersed solid particles. Of these, the most harmful to the environment and humans are: carbon monoxide (CO), hydrocarbons (CnHm), nitrogen oxides (NOx) and soot particulate matter. Major automotive companies and research institutes are working to reduce harmful emissions from internal combustion engines of both gasoline and diesel. Work is also at progress at the Voronezh State Agrarian University named after Emperor Peter I at the Department of Agricultural Machines, Tractors and Cars. Employees of the department have developed several diesel particulate filter designs, which are protected by patents of the Russian Federation.

Porous ceramics used as a filtering material in modern particulate filters has a number of disadvantages (uneven pore diameter of the filtering material, pore melting, low soot capacity, etc.), which leads to a significant increase in its resistance in the exhaust system, reduction in power, increased maintenance costs. For capturing soot particles as a filtering material, it is proposed to use porous mesh
material (PMM); two samples were chosen, the P300 plain weave mesh and the one-sided twill mesh C685.

2. Materials and methods
In the theoretical consideration of the process of trapping solid particles by this filtering material, the following assumptions were made: the electrical, thermal, and gravitational forces were neglected since they are insignificant in this process. The process of capturing solid particles is carried out due to the forces of inertia 1, tangency 2 and diffusion 3. Figure 1 shows the movement of soot particles in the flow around a single fiber mesh. Under the action of the inertial forces, the particles deviate from the streamline starting with some size, as a result they move near the fiber along a less curved trajectory and pass so close to it that they are captured even when the streamline along which they initially moved, lies at a distance greater than the radius of the particles [2, 4].

![Figure 1. Scheme of soot particles trapping by single fiber mesh: 1 – the mechanism of tangency of the particle; 2 – inertial mechanism of particle capture; 3 – diffusion mechanism for trapping soot particles.](image)

The probability of the collision of soot particles with a single fiber under the action of inertial forces is a function of the Stokes number (Stn) and is expressed by the formula [1,2]:

\[
St_n = \frac{d_s^2 \times r \times w_0 \times c}{18 \times m \times d_m},
\]

where \(\rho_s\) is the density of soot particles, kg/m³; \(c\) – Koeningham-Milliken correction; \(w_0\) – particle flow rate, m/s; \(d_m\) – wire diameter mesh, m; \(\mu\) is the dynamic viscosity of the exhaust gas, Pa·s.

The larger the Stokes number, the greater the number of collisions of particles with the fiber surface of the filter material. On this basis, the trapping ability of a single layer of the mesh in a PMM filter element depends on the wire diameter, porosity and filtration rate when cleaning exhaust gas from solid particles. The purification degree of exhaust gases from solid particles due to inertial forces for a single PMM layer is determined by the formula [1]:

\[
\eta_{in} = \frac{St_n^2}{St_n^2 + 0.77 \cdot St_n^{1.5} \cdot P^{0.9} + 0.22 \cdot P^{1.6}},
\]

where \(P\) is the porosity of the material.

The degree of cleaning (\(\eta_k\)) due to the forces of contact can be determined by the expression [2]:

\[
\eta_k = \left(1 + \frac{d}{d_m}\right)^{-1} \left(1 + \frac{d}{d_m}\right).
\]

Particle trapping efficiency by tangency is significantly affected by the particle size and diameter of the wire mesh and, to a lesser extent, the flow rate and the viscosity of the gas.

The degree of purification of exhaust gases from solid particles by diffusion can be calculated by the Langmuir equation [2]:
\[
\eta_d = \frac{1}{2.002 \ln \text{Re}} \left( (1 + Z) \ln(1 + Z) - \frac{Z (2 + Z)}{2 (1 + Z)} \right),
\]

(4)

where \( Z \) is the diffusion parameter. The trapping ability due to particles diffusion is insignificant and depends on the size of the particles; the degree of purification increases with a decrease in a particle size, an increase in exhaust gas temperature and a decrease in speed.

The calculation of the degree of purification of exhaust gases from solid particles, in which several mechanisms for the capture of particles and for several layers of PMM operation, is determined by the expression:

\[
\eta_{\text{frac}} = 1 - \left( (1 - \eta_m) \cdot (1 - \eta_k) \cdot (1 - \eta_d) \right)^N,
\]

(5)

where \( \eta_{\text{frac}} \) is the partial efficiency of exhaust gas cleaning from solid particles with a diameter \( d \) by a PMM filter; \( N \) is the number of grid layers.

The partial degree (\( \eta_{\text{frac}} \)) of exhaust gas purification from solid particles through several mesh layers of a PMM filter (\( N_l \)) increases with decreasing wire diameter and porosity of this layer, as well as increasing the filtration rate and the number of mesh layers.

The total efficiency of the exhaust gas cleaning is determined by summing the fractional efficiency over particle size from the expression:

\[
\eta_k = \sum_{n=0}^{n=\infty} \eta_{\text{frac}} \cdot dy(d_p),
\]

(6)

where \( y(d_p) \) is the mass fraction of particles in the exhaust stream.

3. Results and discussion

The PMM efficiency of capturing soot particles has been confirmed by tests conducted at the department of tractors and cars. The tests were carried out in the department laboratory of the department at the test brake bench, equipped with a diesel engine D-243 in accordance with GOST. To measure the smoke content of a diesel engine equipped with a particulate filter (SF), special measuring equipment was used. The efficiency of exhaust gas cleaning by the filter was estimated by the degree of neutralization of toxic substances \( \eta \) [5].

Figure 2 shows the dependence of the exhaust gas purification coefficient on the soot \( \eta_c \) of the D-243 diesel engine, on the crankshaft speed according to the external speed response.

![Figure 2](image)

Figure 2. The external speed response dependence of the soot cleaning efficiency (\( \eta_c \)) of the exhaust gas of the D-243 diesel engine on the filtration rate (\( \omega_0 \)):
1 – soot cleaning degree for the two-layer C685 grid; 2 – P300 soot cleaning degree for three-layers; 3 – P300 soot cleaning degree for two layers.

From Figure 2, the efficiency of cleaning from soot (\( \eta_c \)) when the diesel engine is working on the external speed characteristic was 90-94% for the C685 grid, 83-92% for the P300 grid with three layers, 71-82% for the P300 grid with two layers.
The results of calculating the efficiency of exhaust gas cleaning from soot ($\eta_C$) depending on the material parameters are represented by dashed lines in Figure 2. A comparative analysis of theoretical and experimental dependencies shows that at rotational frequencies from 2250 to 1400 min$^{-1}$, which correspond to the filtration rate respectively, 0.72–0.5 m/s, the convergence of theoretical and experimental dependencies is high and amounts to 96.5%. In the frequency range from 1400 to 1200 min$^{-1}$, which corresponds to a filtration rate of 0.5–0.43 m/s, respectively, the convergence of theoretical and experimental values was 87%. This is explained by the fact that in the calculation of efficiency, changes in the dispersed composition of soot in these operation modes of are not taken into account, the larger soot particles.

![Figure 3](image.png)

**Figure 3.** The dependence of the change in filter resistance on the exhaust gas flow.

It can be seen from figure 3 that the filter resistance has a linear relationship; the gas-dynamic resistance increases with an increase in the exhaust gas flow rate. At an exhaust flow rate of 240 m$^3$/h, the filter resistance is 3.0 kPa; it reaches 4.1 kPa at 310 m$^3$/h.

4. Conclusion

Theoretical calculations and bench tests of a particulate filter equipped with the PMM filter have shown that the efficiency of trapping soot particles was 64 ... 81%, the resistance at the nominal engine speed was 3.6 kPa.

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