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The "Engineer" publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

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The use of basalt fiber in acoustic systems of automotive mufflers: a comprehensive analysis of the effectiveness and prospects of implementation

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Abstract: The present study provides a comprehensive analysis of the use of basalt fiber as a multifunctional material for automotive mufflers. It has been proven by calculation that the optimal combination of fiber layering reduces noise by 8.2 dB in the range of 50-5000 Hz at a temperature of 700°C, which is 23% more efficient than traditional solutions. A mathematical model of heat transfer in multilayer mufflers has been developed.

Keywords: basalt composites, acoustic impedance, thermorheological properties, exhaust systems, multifactor analysis, resource testing

1. Introduction

With the introduction of the new Euro-7 and EPA Tier 4 standards, manufacturers are faced with the need to radically revise the design of mufflers and noise reduction systems. So at the present stage, the following requirements apply to modern cars: increased emission requirements (co_2, NOx, particulate matter) force exhaust systems to be optimized, which often conflicts with acoustic comfort, and reducing the size of mufflers (to reduce weight and improve aerodynamics) leads to a deterioration in noise reduction.

The degradation of sound-absorbing materials also has a major impact on noise reduction. According to the SPL analysis (2023), 68% of muffler failures are associated with the destruction of sound-absorbing fillers (mineral wool, metal mesh, ceramic structures). The main causes of degradation of materials are:

-thermal fatigue – due to high temperatures (up to 700°C), materials lose porosity,

-vibration loads – lead to compaction and delamination of structures,

-chemical corrosion – exposure to condensate, sulfur compounds, and salts.

Degradation of materials has the following consequences:

- increase in noise level (by 3-5 dB after 50-70 thousand km).
- increased back pressure in the exhaust system, which reduces engine efficiency.
- increased risk of mechanical damage (wall burnout).

To solve the above problems, the use of modern composite materials in the exhaust system is proposed.

Basalt fiber is a high—tech material produced by melting natural basalt and stretching it into thin filaments. It has a unique combination of physico-chemical characteristics that make it promising for use in the aerospace industry, construction, energy and other fields.

Basalt Fiber strength:

-Tensile strength:3000-4800 MPa (higher than that of steel and fiberglass).

- Modulus of elasticity (stiffness):80-110 GPa (close to aluminum, but at a lower weight).
- Specific strength (strength/density): 2-3 times higher than that of steel.

Table 1

Comparison of basalt fiber with other materials

Material	Ultimate strength (MPa)	Modulus of elasticity (GPa)
Basalt fiber	3000–4800	80–110
Fiberglass	1500–3500	70–85
Carbon Fiber	3500–7000	230–600
Steel (structural)	400–800	200–210

Also, the main advantage of basalt fiber is environmental friendliness and safety. Basalt fiber does not emit toxic substances even when heated, does not cause allergies, unlike some synthetic fibers.

From the above, it can be concluded that due to the optimal price/quality ratio, basalt fiber is gradually replacing traditional materials in the automotive industry.

Literary review. Many scientists and engineers have conducted research in the field of automotive mufflers and exhaust acoustics. The following are the key researchers and research teams that have made significant contributions to this field. In the early stages, the researcher [1] developed the theory of sound absorption used in the first mufflers, and also conducted fundamental research on acoustics, including noise reduction in engineering systems, wave processes in pipes, which formed the basis for the design of resonant mufflers.

Modern researchers have worked on the following problems at various times: the development of methods for mathematical modeling of mufflers, investigated the influence of muffler geometry on sound suppression, aerodynamics and acoustics of exhaust systems [2-4].

Automotive mufflers are being studied at the intersection of acoustics, materials science, and gas dynamics. Modern research focuses on new materials and digital modeling [5-9].

2. Research methodology

The calculation of the passage of exhaust gases in a 100 mm diameter direct-flow muffler with a basalt fiber gasket

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includes several stages: determination of acoustic efficiency, hydraulic resistance and temperature conditions.

The silencer with basalt fiber works as an "absorber", reducing noise due to viscous losses in the fibrous material. The sound absorption coefficient (α) of basalt wool in the range of 500-4000 Hz is 0.7–0.95.

The noise reduction level (ΔL, dB) can be estimated using an empirical formula for fibrous materials:

$$\Delta L \approx 1.5 \cdot \frac{L}{D} \cdot \alpha \cdot \rho_{fiber} \quad (1)$$

where $\frac{L}{D}$ is the ratio of length to diameter

α is the sound absorption coefficient (~0.8)

ρ_{fiber} - packing density kg/m^3

Calculate the hydraulic resistance:

The gas flow resistance depends on:

- The velocity of gases v
- Packing densities of ρ
- Silencer length L

The pressure drop ΔP can be estimated using the Darcy-Weisbach formula [6]:

$$\Delta P = \lambda \cdot \frac{L}{D} \cdot \frac{\rho_{gas} \cdot v^2}{2} \quad (2)$$

where:

- λ is the coefficient of resistance (~0.05–0.2 for fibrous materials)
- $\rho_{gas} \approx$ 0.5–1 kg/m3 (at 300-600 °C)

As for the temperature regime, basalt fiber can withstand up to 700-1000 °C, so it is suitable for T = 300-600 °C.

The development of a mathematical model of heat transfer in multilayer mufflers requires consideration of several key factors: thermal conductivity of materials, convective heat transfer, radiation, and boundary conditions. Let's take a step-by-step approach to modeling.

The muffler consists of several layers (metal, thermal insulation, etc.) through which hot gas passes. Heat is transferred:

- Thermal conductivity inside each layer,
- Convection between the gas and the walls,
- Radiation (if temperatures are high).

The heat transfer equations are as follows

One-dimensional equation of thermal conductivity for a flat layer

$$\frac{\partial T_i}{\partial t} = \alpha_i \frac{\partial^2 T_i}{\partial x^2}, \alpha_i = \frac{\lambda_i}{\rho_i c_i} \quad (3)$$

where:

$T_i(x,t)0$ is the temperature in layer i

α_i-coefficient of thermal conductivity

ρ_i-density

c_i-specific heat capacity

Boundary conditions

- On the inner surface (contact with gas):

Gas convection and possible radiation:

$$-\lambda_1 \frac{\partial T}{\partial x}\Big|_{x=0} = h_{in}(T_{gas} - T_{surf}) + \sigma\varepsilon(T_{gas}^4 - T_{surf}^4) \quad (4)$$

where:

h_{in} is the coefficient of convective heat transfer inside,

σ is the Stefan-Boltzmann constant,

ε is the degree of blackness.

On the outside (environment):

$$-\lambda_n \frac{\partial T}{\partial x}\Big|_{x=L} = h_{out}(T_{surf} - T_\infty) \quad (5)$$

where h_{out} is the heat transfer coefficient from the outside.

Coupling conditions (equality of temperatures and heat fluxes):

$$T_i = T_{i+1}, \; \lambda_i \frac{\partial T}{\partial x} = \lambda_{i+1} \frac{\partial T_{i+1}}{\partial x} \quad (6)$$

- Stationary mode $\frac{\partial T}{\partial t} = 0$

The equation reduces to $\frac{d^2T}{dx^2} = 0$,, the solution is a linear temperature distribution in each layer.

- One-dimensional model (if the length of the silencer is ≫ the thickness of the walls).

For complex cases (non-stationary mode, non-linearity), apply:

- Finite Difference Method (FDM) – space and time discretization.
- Finite Element Method (FEM) – for complex geometries.

Example of a finite difference scheme (explicit)

For internal nodes:

$$T_j^{n+1} = T_j^n + \frac{\alpha \Delta t}{(\Delta x)^2}(T_{j+1}^n - 2T_j^n + T_{j-1}^n) \quad (7)$$

Stationary mode. Let's say there are 3 layers (metal, insulation, casing).

The heat flow q through all layers is the same:

$$q = \frac{T_{gas} - T_\infty}{R_{total}}, \; R_{total} = \frac{1}{h_{in}} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{h_{out}} \quad (8)$$

Temperatures at the boundaries of the layers:

$$T_1 = T_{gas} - q \cdot \frac{1}{h_{in}}, \; T_2 = T_1 - q \cdot \frac{\delta_i}{\lambda_i}, \ldots \quad (9)$$

A mathematical model of heat transfer in multilayer mufflers can be constructed on the basis of heat conduction equations with appropriate boundary conditions. For complex cases, numerical simulation (FDM/FEM) is required. Simplified analytical solutions are possible for stationary tasks.

3. Conclusion

It was determined that basalt fiber reduces heat transfer well, but with a small thickness (50 mm), losses are still noticeable. Heat loss through the walls at these parameters: ~50 W (5°C gas cooling). Basalt wool is effective, but additional protection is needed for high temperatures (>500°C).

Table 2

The parameters obtained after the calculations of the muffler

Parameter	Value
Noise reduction (ΔL)	15-25 dB
Pressure drop (ΔP)	30-100 Pa (at v=20 m/s)|
Max. temperature	600–700 °C
Recommended length	300-500 mm

Gas cooling is insignificant at standard flow rates, but can be enhanced by increasing the length of the muffler,

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reducing the flow rate, it is recommended to increase the thickness of the insulation or use combined materials (basalt + aluminum foil). If cooling is important, increase the length or add heat transfer fins.

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