https://doi.org/10.1051/e3sconf/202236301053

Influence of discrete arrangement of porous filters on pressure drop

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Abstract. One of the problems of the modern world is air pollution by harmful substances contained in the exhaust gases of cars. To solve this problem, diesel, and gasoline porous particulate filters are used. However, it is necessary that the porous filter create a minimum pressure drop while maintaining a high filtering capacity. The purpose of the study is to identify the feasibility of a discrete arrangement of filters to reduce the pressure drop. In this work, we carried out a study to determine the pressure drop in porous filters with porosity values ε=0.75 and ε=0.58. Experiments on measuring the pressure drop were carried out for a different number of filters (from 2 to 5), arranged continuously and discretely.

1 Introduction

One of the main problems of the modern world is environmental pollution with nitrogen oxides, carbon oxides, and particulate matter, which are mainly found in car exhaust gases and cause great harm to the environment and human health. This problem has several solutions: the use of alternative fuels (for example, hydrogen), the development of new technologies for electric vehicles, or the filtering of exhaust emissions. Diesel particulate filters are the most effective and economical method of reducing harmful emissions to the atmosphere (Viswanatha et al., 2021; Tan et al., 2020). Such filters have a porous structure and usually consist of porous minerals such as aluminum titanate, cordierite or silicon carbide. Diesel particulate filters have shown high efficiency in filtering particulate matter in diesel vehicles. However, as soot and ash accumulate in the pores of the filter, the back pressure of the exhaust gases and the fuel consumption of diesel engines increases (Yamamoto, 2018). The large amount of ash captured by the filter increases the pressure drop significantly over time, necessitating periodic filter regeneration (Zhang et al., 2020). In this regard, it is advisable to use filters with a lower pressure drop, which will reduce the frequency of regenerations.

One way to reduce the pressure drop generated by a filter is to optimize its structure. In (Yamamoto, 2018), the authors conducted numerical studies of the pressure drop in a diesel particulate filter at various porosity and pore size values. As a result of the study, the authors concluded that an increase in pore size or porosity leads to a decrease in pressure drop. The

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back pressure in a filter depends on its structure and the flow pattern inside the filter. Gong et al. (2018) conducted experimental studies to determine the filter efficiency and pressure drop in the case of using a porous insert with uniform and non-uniform porosity. Research results have shown that inserts with heterogeneous porosity provide a lower pressure drop than inserts with uniform porosity, while increasing filtration efficiency.

In (Ou et al., 2019), the authors investigated the effect of the metal fiber thickness of a gasoline particulate filter on the pressure drop at various temperatures and exhaust gas mass flows. As a result of research, the authors found that thinner fibers provide less resistance to flow, and are also able to withstand higher exhaust gas temperatures.

Orihuela et al. (2018) investigated the filtration efficiency and pressure drop of a diesel particulate filter made from biomorphic silicon carbide. The studied porous filter sample showed relatively low permeability, however, the filtration efficiency was more than 75% for a clean filter at a pressure drop of 2 to 4 kPa, which corresponds to the values of commercially available diesel filters. However, to reduce the pressure drop, the authors recommend increasing the permeability of the porous filter.

Xiao et al. (2020) proposed a particulate filter design with different cell cross-sectional shapes: triangle, rectangle, and hexagon, and numerically investigated the effect of cell geometry on filtering area and pressure drop. Research results show that a filter with hexagonal cells allows increasing the filtration area and reduce the pressure drop over the entire service life compared to other cell geometries. In addition, the filters with cells in the form of a hexagon makes it possible to reduce the volume of the filter with a constant soot load.

Thus, a large number of studies are devoted to reducing the pressure drop in a porous filter and increasing its efficiency by optimizing structural parameters: porosity, permeability, pore size, etc. (Soloveva et al., 2020; Soloveva et al., 2019; Soloveva et al., 2018; Soloveva et al., 2019). Other directions in improving the efficiency of the filter are the optimization of the thickness of the porous insert, the use of multilayer filters consisting of discrete porous inserts, as well as the optimization of the location of discrete inserts. Xiao et al. (2018) conducted studies on the effect of the thickness of the filter layers of a two-layer filter on the filtration efficiency, the average concentration of solid particles at the outlet and the pressure drop. The thickness of the upper layer varied from 180 to 280 mm, the thickness of the lower layer, from 45 to 85 mm. At the same time, in the case of maximum thicknesses, the filter layers were arranged continuously; at minimum thicknesses, these were two discretely located layers. The research results showed that with the same initial filtration velocity of 0.25 m/s, an increase in the thickness of the upper layer of the filter from 180 to 280 mm makes it possible to increase the filtration efficiency and reduce the average concentration of dust at the outlet, the pressure drop in this case increases slightly. Increasing the thickness of the bottom layer of the filter makes it possible to reduce the concentration of dust at the outlet by more than 2 times, but the pressure drop increases by 70.9%. Thus, the thickness of the filter layers has a significant impact on the pressure drop and filtration efficiency.

The purpose of our study is to determine the influence of the location of discrete porous filter inserts on the value of the pressure drop.

2 Materials and Methods

The study used fibrous filters with porosity $\varepsilon=0.75$ and $\varepsilon=0.58$. Pictures of filters are shown in Fig.1.

https://doi.org/10.1051/e3sconf/202236301053

Fig. 1. Pictures of studied filter samples: (a) filter with porosity value ε=0.75;
(b) filter with porosity value ε=0.58.

As a result of an experimental study, we obtained the values of the pressure drop or various arrangements of porous filters in the channel during air blowing. The scheme of the experimental setup is shown in Fig. 2. A compressor and a rotameter connected in series supplied air to the channel at a fixed velocity (v = 0.25; 0.75; 1 m/s). At each velocity we took five measurements, and the results were averaged. The number of porous inserts varied from 2 to 5. Fig. 2(a) and Fig. 2. (b) shows a continuous and discrete arrangement of porous elements, respectively. A continuous arrangement implies a series connection of porous filters with no distance between them (Fig. 2a). Discrete arrangement implies the arrangement of filters in series, at a fixed distance from each other (Fig. 2b). With a discrete arrangement of filters, the distance between them was equal to the height of the filter and corresponded to a value of 1 cm.

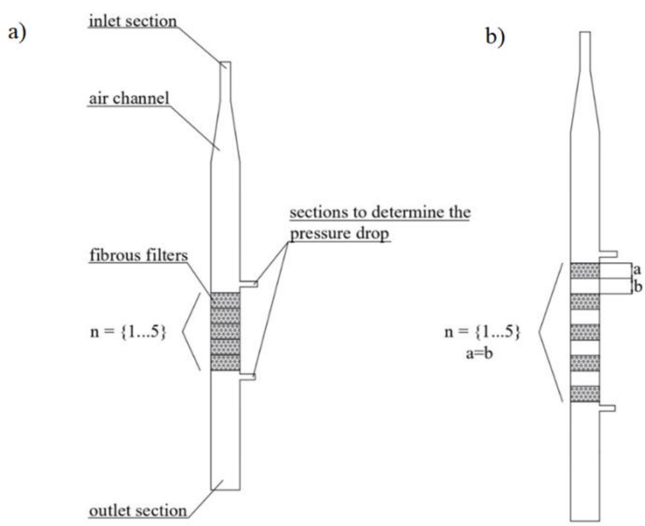

Fig. 2. Scheme of the experimental setup: (a) in the case of a continuous arrangement of filters;
(b) in the case of a discrete arrangement of filters.

3 Results and Discussion

As a result of measurement with the Testo 510i differential pressure gauge, we obtained the values of the pressure drop. The results for filters with porosity ε=0.75 are shown in Fig. 3.

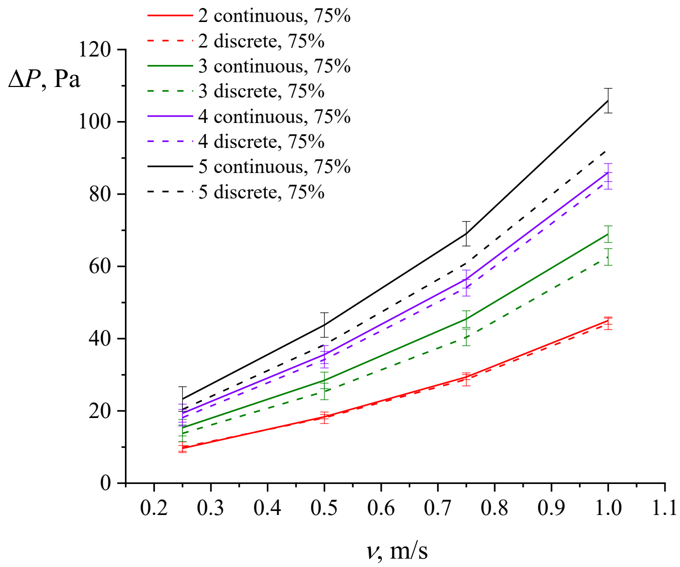

Fig. 3. Change in pressure drop versus velocity for filters with porosity ε=0.75.

From Fig. 3, we can be seen that for the number of inserts from 2 to 5, the value of the pressure drop with a discrete arrangement of filters is noticeably less than with a continuous arrangement. With an increase in the number of filters in the channel, the function $\Delta P(v)$ with a continuous and discrete arrangement of inserts increases faster. At the same time, with the same number of inserts, with their discrete arrangement, the function $\Delta P(v)$ increases more slowly than with a continuous arrangement of inserts. In the case of an equal number of inserts, with an increase in air velocity in the inlet section of the channel, the values of the pressure drop for continuous and discrete arrangement differ by a larger value than at low velocities. For a velocity of 0.25 m/s, the difference in pressure drop was the smallest. The difference in pressure drop also depends on the number of filters in the channel. Thus, the difference in ΔP values increases with the number of inserts. The percentage values for the difference in pressure drop values for discrete and continuous arrangement of filters with porosity ε=0.75 depending on the number of inserts and air velocity are presented in Table 1.

Table 1. The decrease in pressure drop with a discrete arrangement of porous inserts relative to a continuous arrangement, in percent, at a porosity value of ε=0.75.

Number of inserts	**Air velocity, m/s**			
	0.25	**0.5**	**0.75**	**1**
2	3.3%	2.0%	9.2%	12.3%
3	1.5%	10.2%	6.4%	12.5%
4	2.2%	10.8%	4.0%	11.8%
5	2.0%	11.2%	4.2%	12.7%

Figure 4 shows a graph of the pressure drop for filters with porosity ε=0.58.

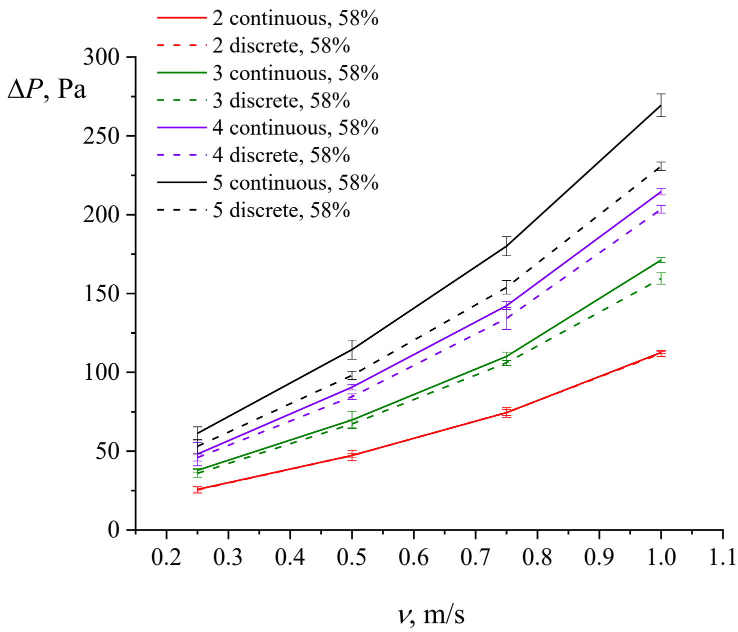

Fig. 4. Change in pressure drop versus velocity for filters with porosity ε=0.58.

Presented in Fig. 4 graphs for filters with porosity *ε*=0.75, the dependencies are similar to the graphs in Fig. 3 for porosity *ε*=0.58.

The percentage difference for discrete and continuous arrangement of filters with porosity ε=0.58 depending on the number of inserts and air velocity are presented in Table 2.

Table 2. The decrease in pressure drop with a discrete arrangement of porous inserts relative to a continuous arrangement, in percent, at a porosity value of ε=0.58.

Number of inserts	**Air velocity, m/s**			
	0.25	**0.5**	**0.75**	**1**
2	1.2%	5.2%	4.6%	13.5%
3	0.3%	3.6%	6.6%	14.3%
4	0.1%	3.8%	5.7%	14.5%
5	0.5%	6.8%	5.2%	14.3%

Analyzing the results presented in Table 1 and Table 2, it can be seen that for filters with higher porosity (ε=0.75) the pressure drop reduction for the discrete arrangement is significantly lower. The percentage difference in pressure drop for filters with porosity ε=0.75 approaches the values for discrete arrangement of filters with ε=0.58 only at higher velocities (0.75; 1; m/s) and with a large number of inserts (n=5). Thus, it can be concluded that at a high value of porosity ε it is less effective to use a discrete arrangement of inserts, it is possible that at a significantly higher value of the porosity of the elements (ε> 90 ... 95%), it is practically impractical to use a discrete arrangement at low flow rates. With an increase in the velocity and increase in the number of sequentially arranged porous elements, an increasing hydraulic resistance is created in the channel, that is, even for filters with high porosity, the use of a discrete arrangement leads to a significant decrease in pressure drop (Table 1).

It is necessary to note that the experimental studies of the resistance during air movement through porous fibrous inserts show a decrease in the measured pressure drop for all cases of discretization of the material compared to continuous inserts of the same length of the porous section. Such an effect can be associated with a highly turbulent air movement between the porous inserts at a discrete arrangement of the elements under study. In the region where the air flow approaches the first porous material, it can be assumed that the gas molecules move, on average, parallel to the axis of symmetry of the tube. At the outlet of the fibrous material, the air flows are not parallel to the axis of symmetry of the tube, and some distance must be traveled to equalize the total flow. Discrete inserts are not far enough apart and the air flow does not have time to equalize when moving between them. It can be concluded that for small values of the porosity of the material, discretization with the formation of stepwise air movement (porous medium – free tube) contributes to a decrease in the total resistance, despite an increase in the total length of the sample.

4 Conclusion

As a result of the study, using the example of porous filters with porosity values of ε=0.75 and ε=0.58, the expediency of using a discrete arrangement of porous inserts in order to reduce the pressure drop was confirmed.

As the air velocity increases, the difference in pressure drop increases for continuous and discrete filter arrangements. The difference in pressure drop between continuous and discrete filter arrangements also increases with the number of filters. With a higher porosity value (ε=0.75), the decrease in pressure drop for a discrete arrangement with a small number of inserts (n= 2; 3) is significantly lower than for filters with porosity ε=0.58. The difference in pressure drop values for ε=0.75 increases with increasing air velocity. The pressure drop values for a discrete arrangement of inserts with porosity ε=0.58 are less dependent on the number of successive filters and air velocity.

Acknowledgments

The research was funded by the Russian Science Foundation, grant number 21-79-10406, https://rscf.ru/en/project/21-79-10406/.

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