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CFD modeling of aerosol flow through a granular filter with porous granules

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Abstract. In this work, we made a comparative calculation of a granular filter with different shapes of the granules. We created granular filter models with solid and porous granules. The diameter of the granules was 5 mm, and the porosity was $\varepsilon = 0,8$. A comparison was made on the deposition efficiency, pressure drop, porosity, and filter quality parameter. We have found that for a filter with porous granules, the particle deposition efficiency is slightly lower than for a filter with solid granules. However, the pressure drop is an order of magnitude higher for a filter with solid granules, which ensures the maximum value of the filter quality.

1. Introduction

The problem of filtering air and waste liquids is becoming increasingly relevant due to the need to reduce the number of pollutants emitted into the environment. In order to optimize filtration technology, it is essential to calculate the filter performance [1-3]. The parameters that determine performance and efficiency are the total pressure drop and permeability, depending on the size of the aerosol particles. Therefore, it is crucial to consider the particle size, thickness, and porosity of the filter. Particles can be removed from the gas stream using cyclones, barrier filters, electrostatic precipitators, granular bed filters, or scrubbers. Choosing a filter to use is a complex task, including estimating the number of emissions, reliability, and required costs. The analysis shows that barrier filters and granular bed filters are the most promising approaches to the purification of hot gas for advanced coal conversion technologies. Granular bed filters are attractive for filtering hot gas because inexpensive, refractory granules are used as the filter medium. A moving-bed granular filter uses continuously moving granular material (gravel or sand) as a filter medium. Since the filter medium is a refractory material, such filters can operate at very high temperatures. Unlike conventional barrier filters, they do not require periodic purging to remove dust deposits, since the dust is continuously removed from the filter with a granular stream. The numerical modeling of granular and open cell foam filters was discussed in [4–6]. Several types of granular filters have been described in the literature [7,8]. Granular filters with a moving bed work according to the principle to which a flowing bed of particles can effectively remove contaminants from the stream. Although this method is up-and-coming for achieving high filtration efficiency, large sizes and high throughput are cited as a disadvantage of granular filters with a moving bed. Filtration in a granular bed can be carried out in four variants: a fixed bed, a periodically moving bed, a continuously moving bed, and a fluidized bed. The flow in a granular filter is usually directed downward by gravity and is controlled from below by a rotating auger or moving belt. The design of the granular filter differs in how the gas enters and passes through the filter. These filters can be classified as cross, direct-flow, and counter-current. However, the interaction of the gas stream with the granular bed requires the presence of walls made of mesh or shutters, which are also prone to clogging. Filter clogging has been studied in civil engineering, soil science, membrane research, and other disciplines for many years; no model currently can predict clogging without using empirically selected parameters. Although at least one attempt has been made to investigate clogging in granular filters [9]. In [10], a granular filter was described in which two distinctive filtering zones were used: the interfacial region, which removed most of the dust from the gas stream, and the stagnant zone, where the gas backflow and granular filtering material made it possible to achieve a very high filtration efficiency. The design and performance of this filter are described in [11-15]. The gas flow in various packings of granules was studied in [16, 17].

2. Problem formulation

Reducing the total resistance and maintaining the efficiency of particle deposition is one of the serious tasks of research in the field of filtration. It is known that the greater value of the porosity of the medium provides the lower pressure drop. Porosity is defined as the ratio of pore volume to the total volume of the filter medium. Significantly changing the porosity (only the size and shape of the granules) is very difficult; therefore, porous granules were created. A model of a porous granule with porosity $\varepsilon = 0{,}8$ is shown in figure 1.

Figure 1. Model of a granule with the porosity $\varepsilon = 0{,}8$.

We used the discrete element method to simulate the mechanical behavior of solid granules under the influence of gravity. For this, we created solid and porous granules with a diameter of 5 mm, from which a region of the filter medium was subsequently formed. The porosity of the filter bed from solid granules is $\varepsilon = 0.6$, the total porosity in the filter model created by the set of porous granules is $\varepsilon = 0{,}92$. The high value of porosity is because when modeling the fixed bed, empty regions are formed due to the specific shape of the porous granules. The steps for creating a granular bed are shown in figure 2.

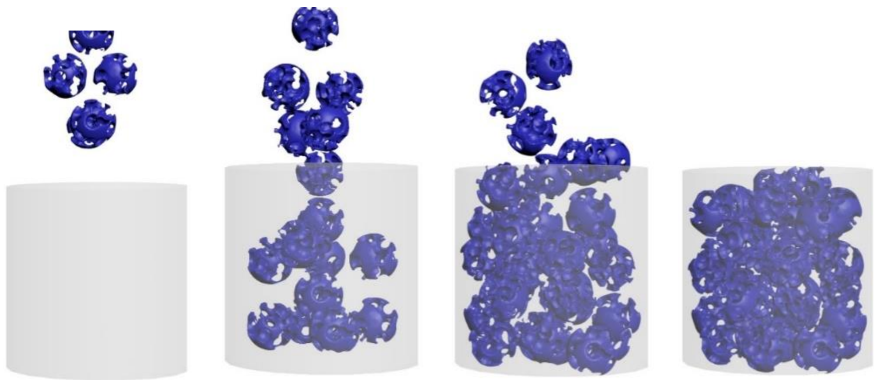

Figure 2. Modeling a granular bed using the discrete element method.

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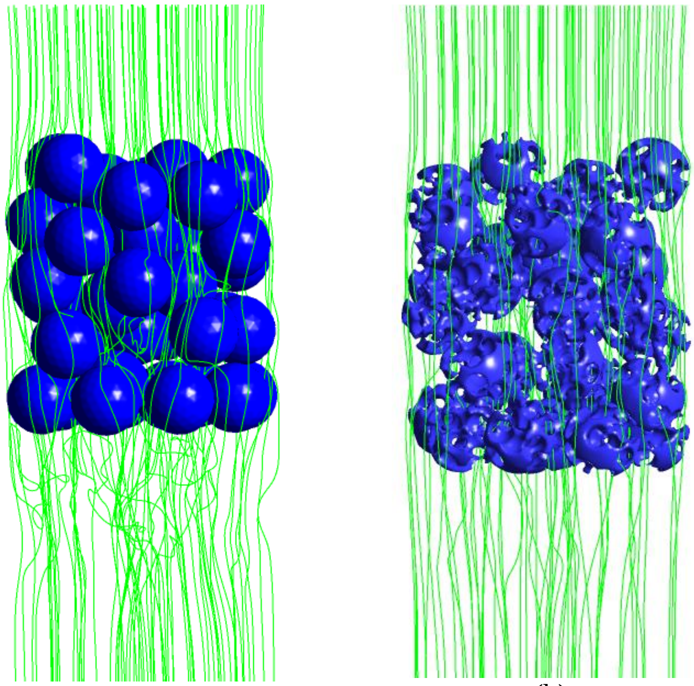
The geometries used to conduct numerical studies are created by obtaining an inverse matrix based on geometric models since the flow occurs in inter-pore space. The size of the filter area is 20 mm in diameter and 20 mm in length. A nozzle with a length of 10 mm is attached on the input side, and a pipe with a length of 30 mm is attached on the output side. The total length of the model is 60 mm. We performed the calculations in the CFD ANSYS Fluent software package (v. 19.0).

3. Results

Figure 3 shows examples of streamlines for two granule packing models for an initial velocity of u=1 m/s. The curvature of streamlines for option (a) is due to significantly higher resistance of the medium.



(a) (b)

Figure 3. Streamlines calculated with solid (a) and porous (b) granules.

We compared the pressure drop values with the values obtained by the experimental equation proposed in [17] to check the correctness of the results of the numerical simulation:

$$S_v = 6\frac{(1-\varepsilon)}{d_p}, \tag{1}$$

$$\frac{\Delta p}{L} = 4{,}17\frac{(S_v)^2}{\varepsilon^3}\mu u + 0{,}292\frac{(S_v)}{\varepsilon^3}\rho u^2, \tag{2}$$

where S_v is specificsurfacearea, ε is the porosity of granular bed, d_p is the diameter of the granule, Δp is the pressure drop, L is the thickness of the filter, μ is the dynamic coefficient of viscosity of a liquid or gas that flows through a filter, $u$is the flow velocity, ρ is density of the gas or liquid.

Figure 4 demonstrates the curves of changes in the pressure drop depending on the average flow rate according to the experimental equation (2). Curves correspond to the case of solid granules with a total packing porosity and for the case of porous granules with a total porosity for the thickness of the porous insert L=2 cm.

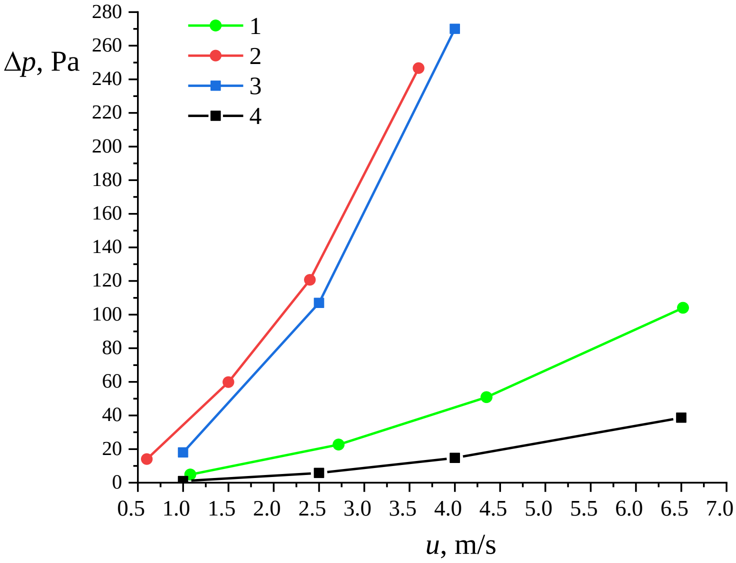


Figure 4. Comparison of pressure drop curves for: 1 – numerical calculation for the model of filter with porous granules, 2 – numerical calculation for the model of filter with solid granules, 3 – results of empirical equation (1) for the case of solid granules, 4– results of empirical equation (1) for the case of porous granules.

The results presented in figure 4 correlate well for the case of solid granules but differ for porous granules. This is due to the fact that equation (2) is not universal, as well as with variable geometry depending on the location of porous granules in space.

Particle deposition efficiency and pressure drop are two main parameters in the formation of the filter quality factor. Figures 5 and 6 show the deposition efficiency and filter quality factor curves for a granular filter with solid and porous granules.

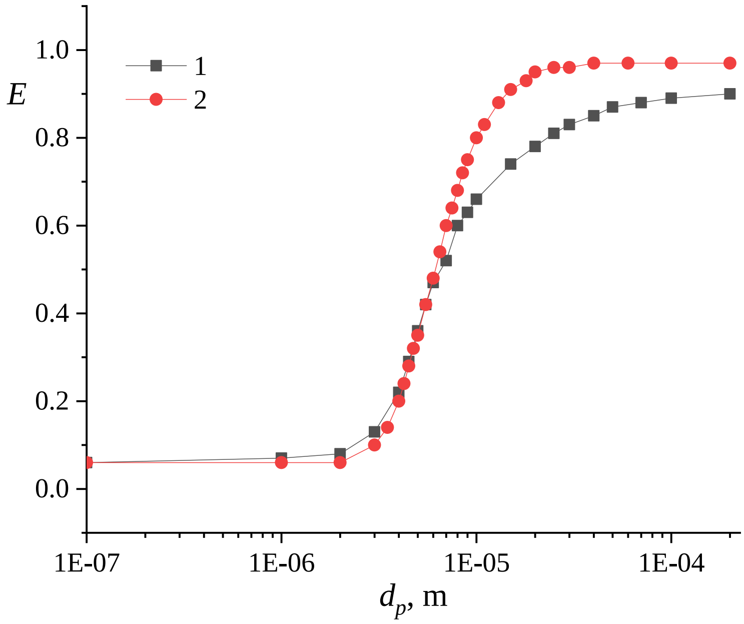


Figure 5. Particle deposition efficiency curves for: 1 – filter with porous granules, 2 – filter with solid granules.

The graphs show that the curve of particle deposition efficiency for a filter with solid granules located higher than in the case of a filter with porous granules. The curves begin to differ only with a particle diameter of 6 μm . This behavior can be explained by the fact that more inertial particles are carried away by the flow through the channels of porous granules. The pressure drop is expectedly higher with a filter with whole granules. The filter quality factor Q_f is determined by the ratio of the deposition efficiency to the differential pressure.

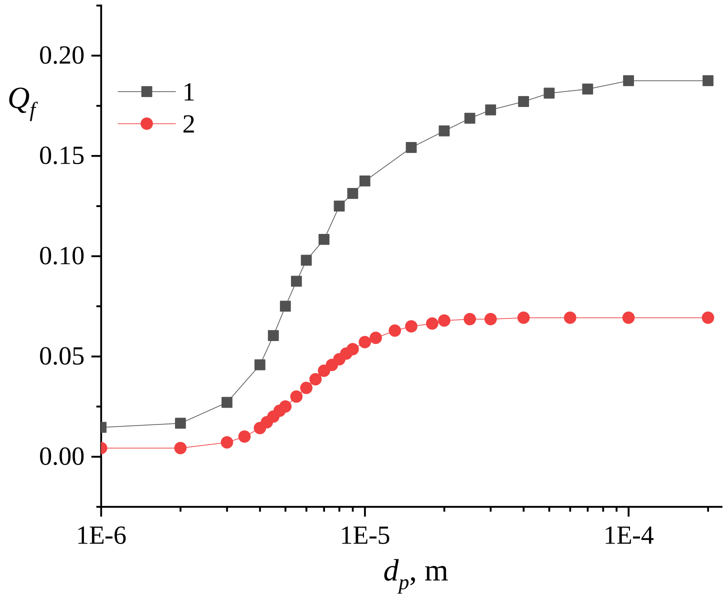


Figure 6. Filter quality curves: 1 – filter with porous granules, 2 – filter with solid granules.

4. Conclusion

We carried out the detailed numerical simulation of the flow of a gas suspension through a porous medium and compared filters with solid and porous granules. Based on the calculations, we can say that it is preferable to use a filter with porous granules since the quality factor is much higher for this filter. With each new simulation of the filtering bed, the porosity of the region can change insignificantly. This is because the granules collide with each other, changing the path of incidence and forming a new geometric region.

Acknowledgments

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