

The determination of hydraulic resistance during laminar filtration through layers of sorbents and ion-exchange granules in environmental mass exchange equipment

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Abstract. The paper presents main calculation dependencies, their advantages and disadvantages for calculating the hydraulic resistance of granular and porous layers in the area of low filtration rates. Approaches are given to account for the influence of porosity and size of particles (sorbent granules) that differ in the values of constants and different ways to account for the influence of particle shape on the hydraulic resistance of the granular layer.

1 Introduction

Filtration flows are used in many industrial processes and products of various branches of mechanical engineering, in technologies and equipment of the chemical industry and related industries [1-17]. Filtration is used in water treatment processes and in environmental technologies [18-41]. Filtration processes are an integral part of the hydrology and technologies of oil and gas production [42, 43]. Filtration flows are also implemented in a wide range of environmental mass transfer equipment, in such processes as adsorption, desorption, ion exchange, etc. [44-73].

The hydraulic resistance of the porous layer is an important technical characteristic of devices that operate using filtration flows (adsorption, ion exchange, drying, filtration, flow of gas and liquid-phase reaction products through the porous layers of the catalyst, etc.). The main purpose is determination the hydraulic resistance of a porous layer, so it is necessary to have equations approximating the filtration curve as a dependence of the pressure gradient on the filtration rate $\Delta P/H=f(v_f)$, or criterion equations for determining the coefficient of hydraulic resistance of a granular layer, followed by determining its hydraulic resistance using the modified Darcy-Weisbach equation for filtration flow in a porous layer.

Usually, when you are performing engineering calculations, it is necessary to determine the hydraulic resistance of the porous layer in a limited range of possible changes in the filtration rate. This range of filtration rate can be located in the area of a linear section of

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the filtration curve, within its nonlinear section, or at the same time partially belong to the linear and nonlinear sections in the area of their interface.

2 Methods and materials

Let's consider the determination of the hydraulic resistance of a porous layer for the area of a linear section of the filtration curve using approximating dependencies. The mode of filtration flow within a linear section of the filtration curve is usually called laminar filtration. This mode of filtration flow is found, for example, in such processes as adsorption, ion exchange processes, fine cleaning of liquids using thin-pore volumetric filter partitions, etc.

The approximating equation is the dependence where k is the permeability of the porous layer and μ is the viscosity of the liquid for a linear section of the filtration curve (for laminar filtration) based on Darcy's law

$$\frac{\Delta P}{H} = \frac{1}{k} \mu v_f \quad (1)$$

It is necessary to Express the parameters that characterize the structure of the porous layer to use this dependence in the calculation practice. The variety of structures of the porous layer also generates the existence of different forms of this equation. The dependencies expressed in terms of the structural parameters of the porous layer are known as the Kozeny-Carman equations. In the field of chemical technology, the Kozeny-Carman equations for granular porous media obtained using a capillary model of the structure of a porous material have become widespread.

The widely used Kozeny-Carman equation for a granular layer is known, obtained in the framework of the capillary model, when the flow of liquid in the channels of the model is considered by analogy with the Darcy-Weisbach equation [74]

$$\frac{\Delta P}{H} = 150 \frac{(1-\varepsilon)^2}{\phi^2 \varepsilon^3 d^2} \mu v_f, \quad (2)$$

where ε is the porosity of the layer, $d=d_{sphere}$ is used for a layer of spherical particles and $d_{e.d.}$ is the equivalent diameter of particles whose shape is different from the ball. A $d_{e.d.}$ is the diameter of such a spherical particle is assumed, the volume of which is equal to the volume of a particle of irregular shape; ϕ – the shape factor, usually called the shape coefficient. The coefficient "150" included in formula (2) is called the Kozeny – Carman constant. However, the value of this coefficient is not constant and can vary from "150" to "200" [75]. One of the reasons for its low values may be an incorrect estimate of the shape factor (coefficient), which is defined as the ratio of the surface of the ball, which is equal in volume to the particle, to the surface of this particle. Its value, as you can see, is not difficult to calculate for particles of any shape. And differences of different authors on the estimation of the value of the form factor (coefficient) in determining the hydraulic resistance of a granular layer made of the same material can cause discrepancies in the calculation results at the assumed constant value of the Kozeny – Carman constant.

In the paper [76], the flow in the channels of the capillary model is considered by analogy with the Poiseuille equation. The resulting dependence is a generalized Kozeny-Carman equation that is valid for filtration flow in any type of porous layer, regardless of its internal structure

$$\frac{\Delta P}{H} = K \frac{\sigma^2}{\varepsilon^3} \mu v_f, \quad (3)$$

where K is the Kozeny-Carman constant, σ is the specific surface area of the porous layer, related to the unit of its volume. Expressing in this equation the specific surface of a granular layer in terms of its particle diameter and porosity as

$$\sigma = \frac{6}{d(1-\varepsilon)},$$

the Kozeny-Karman equation for a granular layer is obtained as a dependence

$$\frac{\Delta P}{H} = K \frac{36(1-\varepsilon)^2}{\varepsilon^3 d^2} \mu v_f, \quad (4)$$

where, as in the equation (2), $d=d_{sphere}$ is used for a layer of spherical particles and $d_{e.d.}$ is the equivalent diameter of particles whose shape is different from the ball.

As can be seen in equations (2) and (4) are equally considering the influence of porosity and particle size, differ in the values of constants and in a different way of accounting for the influence of particle shape on the amount of hydraulic resistance of the porous layer.

In the equation (2) there are the influence of particle shape is taken into account using the shape factor (coefficient). This coefficient is absent in the formula (4) and the influence of the particle shape is taken into account by the Kozeny-Carman constant " K " in a complex composition with other factors that are not explicitly taken into account. Constant Kozeny-Pocket in the equation (4), in contrast to the constant in the equation (2) is variable and its value depending on the particle shape, the particle size distribution, the method of laying particles and the range of variation of porosity of the granular layer is determined in accordance with the recommendations outlined in the paper [76].

3 Conclusions

The results of processing a large array of the most reliable experimental data from various authors to determine the constant " K " for granular layers consisting of particles of different geometric shapes are presented in the form of tables and extensive text material. Recommended values of the constant " K " for some types of granular porous media are also specified. Thus, for a monodisperse layer of spherical particles in the range of porosity values $\varepsilon=0.38-0.41$, the constant values can be within the range $K=4.2-4.8$ with its most reliable value K equal to 4.55. For a monodisperse layer of regular non-spherical particles (cubes, cylinders, prisms, disks) and shaped attachments (Raschig rings, Berl saddles, Lessing rings, steel springs), the values of the constant K do not depend much on the shape of the particles and attachments, and in the porosity range $\varepsilon=0.33-0.4$ in most cases is within $K=4.6-4.8$. For a monodisperse layer of irregular-shaped particles, such as rounded particles with a smooth surface $K=4.8$. For rounded and cylindrical particles with a rough surface (activated carbon, sorbents, catalysts) and particles with a sharply irregular shape (crushed stone, crushed coal, catalysts for the synthesis of ammonia), the most likely value is the constant $K=5$. If a more precise value of the constant K is required for performing calculations, then it should be determined experimentally in accordance with the recommendations set out in the paper [76].

There is no such amount of detailed information and recommendations for determining the particle shape factor (coefficient) for equation (2), which makes it very difficult to use it for practical calculations. In this regard, it should be considered that equation (4) is more preferable for practical use.

In the well-known Ergun equation, the Kozeny-Carman equation (2) is used to determine the hydraulic resistance of a granular porous layer under nonlinear filtration conditions (figure 1). Obviously, because of the above, replacing this equation with the Kozeny-Carman equation in the form (4) will increase the accuracy of calculations performed using the Ergun equation. The generalized modified Ergun equation is written as

$$\frac{\Delta P}{H} = K \frac{\sigma^2}{\varepsilon^3} \mu v_\phi + \zeta \rho v_\phi,$$

where ζ is the ripple coefficient that takes into account the structure of the porous layer and the contribution of the inertial component of the filtration flow structure.

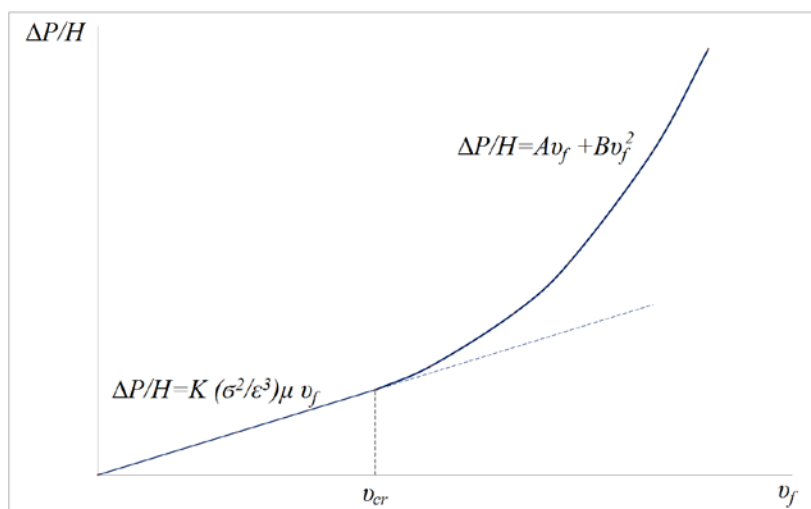


Fig. 1. The filtration curve with selected mode sections of laminar (linear) and transient (nonlinear) filtration.

The dependence (3) can be used to determine the hydraulic resistance of a porous layer consisting of a fibrous, mesh, sponge, or other porous non-granular material, but there is no information about the value of the Kozeny-Carman constant.

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