Assessment of Effect of Gas Permeability Coefficient on Anisotropy of the Porous Material

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Abstract: *The results of experimental studies in the field of the permeability of porous materials with respect to the gas flow are presented. For this purpose, the different coal chars with anisotropic slotted porous structure have been used, and also - for comparison - model materials such as pumice and sintered polyamide. The tests were carried out on a specially prepared measuring set-up with the purpose of measurements of gas permeability with respect to the three flow orientations referring to symmetrical specimens in the cubic form. The results of the measurements showed that there is a considerable effect of the flow directionality on the permeability of coal chars, which results from their internal anisotropic structure. The permeability coefficient was defined, and the experimental assessment of the value of this coefficient against the gas flow and the pressure drop on a porous bed is presented.*

Keywords: *anisotropy, coefficient of effective permeability, frame-structured porous material, biogas, raw gas*

1. Introduction

Gas flow through media with porous structures takes place in many process areas. It is most often associated with filtration or gas flow through filling layers as a porous medium with a loose composition. This type of flow is also included in the technological processes involving the thermal processing of coal and also during the migration of natural gas (e.g., methane) through natural formations, or the flow of reactive gas through various kinds of coal char, such as coke, activated carbon, etc. [1, 2]. In some technological processes, the operation of apparatus and gas flow occurring in them depends on the type and design of gaseous phase dispensers, which are very often made from porous materials.

In each case, the recognition of gas flow conditions through a porous media carries significant problems with the description of hydrodynamics and the assessment of the mechanism of gas flow through porous media, especially in the context of their varied internal structure. On the other hand, the knowledge of these mechanisms allows us to assess the process conditions associated with the hydrodynamics of gas flow through such types of material, and, consequently, the detailed description of hydrodynamic phenomena accompanying the flow of gas through porous media.

Each porous medium is characterized by a given porosity, and its flow structure depends not only on this porosity but also on the size (diameter) of tubules (pores) and their shape - at the given length of the pore. Another specific feature of porous materials is associated with their ability to store and transport of fluids as results of internal and external forces. A study by Aksielrud and Altszuler [3] contains a statement that gas flow through porous media with the pores size of millimetres and less is dominated by the process phenomena resulting from the flow hydrodynamics of viscous fluid whereas inflows through structures with a very small pore size, e.g., tenths of a micrometre, these phenomena are restrained by the physiochemical and diffusive mechanical influences that take place at their interface. This is confirmed by other studies [4, 5], where the disparity between these phenomena decreases in the conditions when a high intensity of gas movement is maintained. Nonetheless, in each case, the gas flow mechanism is closely related to the geometric structure of porous layer. Therefore, it depends on the configuration and the pore size, as well as on their shape and sinuosity. In the general assumption, two major cases of fluid flow in porous media could be distinguished, as it is shown in Fig. 1.

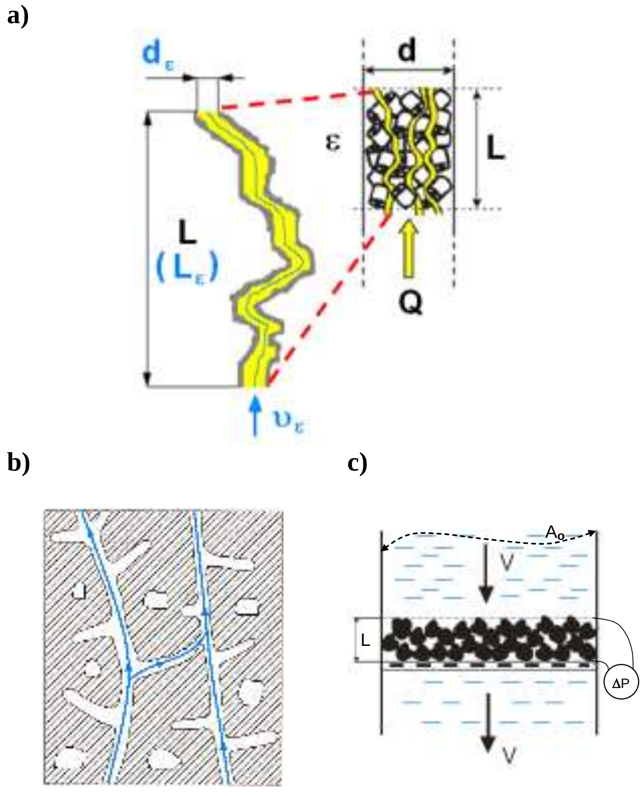

Figure 1: Flow scheme through a porous bed [6]:
a) grain layer with tortuous channels;
b) rigid skeletal structure with open flow channels and blind pores and closed to the flow;
c) Darcy's model

The first one occurs for the case of the flow through a grained layer, while the other one concerns a porous material with a solid (skeletal) structure with empty pores. The first case (Fig. 1a) involves the flow in the space between the grains, and we can assume that the space resulting from the porosity of packed bed layer (ε) is completely available for the fluid flow. Whereas, in the second case (Fig. 1b), the flow occurs only in the area of the pores and channels of open and interconnected, with a surface of flow much smaller than that required by the absolute porosity of the material.

An additional complexity of hydrodynamics stems from the fact that skeletal structures are compact (rigid) deposits that are not able to be relaxed during pressure increase in the system. As a consequence, the flow conditions through such structures will be different from each other, and the flow deviation will be greater than greater the porous sinuosity and content of closed or blinded pores. Lambe and Whitman [7], among others, point out that the measure of this deviation can be coefficient of pressure drop which value corresponds to the bed porosity (ε), the hydraulic diameter of the pores (dε), and the real flow path (L_ε), which results from the sinuosity of the tubular pores.

The basis for a detailed analysis of fluid flow in porous media is still Darcy law. In its original form, this law describes the conditions for permeability of various kinds of grained bed by reference to the filtration mechanism during the laminar flow of water through a sand layer, which constitutes a model grained medium (Fig. 1c). If the variability of liquid properties is taken into account the, the velocity through a porous bed will be proportional to the change in density (ρ) and inversely proportional to the change in viscosity (η) [8]. Then the Darcy equation describing the permeability (Q) of the porous bed takes the following formula

$$Q = K A_o \frac{\rho \hat{g}}{\eta} \frac{\Delta h}{L} \tag{1}$$

where K - coefficient of vertical permeability, m^2; A_o - layer bed cross-section, m^2; ρ – density, kg/m^3; g – earth acceleration, m/s^2; Δh - denotes pressure drop, Pa; η – viscosity, Pas; L - height of porous medium, m;

This formula remains one of the characteristics of the contemporary description of this phenomenon, although it refers only to laminar flow.

The K coefficient in equation (1) describes the so-called permeability of a porous medium, and its value, as shown by the Darcy model, is characteristic of a given porous medium.

Since this coefficient (by definition) has a surface dimension, its value from a hydrodynamic point of view – as characteristic dimension – is very often considered as a certain geometric feature that characterizes the total permeability of the porous material. On the other hand, the value of such permeability depends not only on filtration characteristics of the porous medium (its structure, particle size, their density, porosity, etc.) but also on the physical properties of the fluid, especially its viscosity [9]. As a rule, this factor does not depend on the shape and size of the bed itself.

Of course, the Darcy model also applies to the description of pressure flows. Then for equation (1) we will get

$$Q = K A_o \frac{\Delta P}{\eta L} \quad \Rightarrow \quad K = \eta \frac{Q}{A_o} \frac{L}{\Delta P} \tag{2a}$$

The last equation shows that for a given volumetric flow rate (Q) the permeability of a porous bed could be determined by means of experiments if the fluid properties (η) and the geometrical parameters of the flow system (A_o) are known. The pressure drop (ΔP) on the bed is then experimental value.

If the hydrodynamic parameters are known (flow rate, pressure drop, material porosity and type of gas of course), the permeability coefficient value may be determined by means of experiments. Then relationship (2b) can be written as:

$$K = \frac{Q}{\sqrt{\frac{\Delta P_{zm}}{\rho}}} \tag{2b}$$

where K - coefficient of permeability, m^2; Q - volumetric flow rate, m^3; ΔP - pressure drop, Pa; ρ – density, kg/m^3.

2. Materials and method

The permeability research was conducted some diversified types of materials, the average porosity of which ranged from 22% to 56%. Most of them were coal chars (cokes) from the thermal processing of hard coal, and there are also materials like partially melted waste rocks (including volcanic ones), natural and synthetic pumice and porous agglomerate. The research material comprised various types of stable frame structures thoroughly analyzed in the study by Wałowski and Filipczak [10].

2.1 Experimental stand

To obtain the research objective, the detailed experimental tests were conducted to assess of porous material anisotropy and its effect on the gas permeability of porous materials with the diversified structure and the diversified process characteristics [2].

The research was conducted on a specially-designed stand [11], the fundamental component of which is the flow channel inside which the porous material sample is inserted, Fig. 2a.

a) **b)**

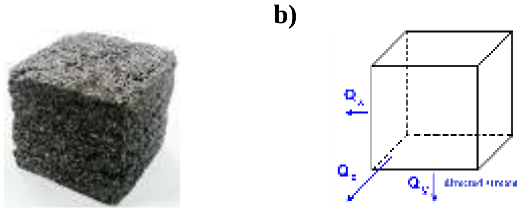

Figure 2: Sample of research material [10]: a) 20 x 20 x 20 mm porous material, b) diagram of the gas flow through the sample

The tested samples were cubic, and the structure of the flow channel enabled measuring the gas permeability for each of the main flow directions (X, Y, Z) (Fig. 4b) through rotating the cubic sample in the selected plane of the measuring cell [10]. The gas permeability research was conducted by using air as a working medium.

2.2 Scope and research methodology

The permeability measure was assumed to be a gas volume flow resulting from the allowable differential pressure forcing the gas flow on a given axis on the porous material sample.

3. Results and discussion

The significant feature of the porous deposit that directly results from its structure is anisotropy of the porous material and its influence on its permeability. As for its definition, this feature is identified with the so-called coefficient of anisotropy [12, 13, 14], which is described as the root of the quotient of the permeability coefficient determined concerning the mutually perpendicular flow planes (3):

$$\beta = \sqrt{\frac{K_h}{K_v}} \quad (3)$$

where: β – anisotropy coefficient; K_h - coefficient of horizontal permeability, m^2; K_v - coefficient of vertical permeability, m^2;

In specific hydrodynamic conditions, this coefficient deviates from the gas flow uniformity that results from a particular flow direction - an increase in the value of this coefficient leads to a decrease in deviation from the anisotropic structure of the porous deposit.

For the horizontal plane (Fig. 3) the permeability coefficient K_h (4):

$$K_h = \sqrt{K_X K_Z} \quad (4)$$

where: K_h - coefficient of horizontal permeability, m^2; K_X - coefficient of permeability in the X direction, m^2; K_Z - coefficient of permeability in the Z direction, m^2;

is most frequently determined as the geometrical average from the value of the permeability coefficient in two horizontal directions, i.e., K_X and K_Z.

On the other hand, the permeability coefficient for the vertical plane K_v (5):

$$K_v = K_Y \quad (5)$$

where: K_v - coefficient of vertical permeability, m^2; K_Y - coefficient of permeability in the Y direction, m^2;

is the value resulting from the flow of gas towards the Z axis

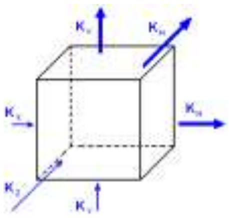

Figure 3: Marking of flow directions and their referring calculation planes of permeability coefficient - horizontal K_h and vertical K_v

Analysis of the anisotropy degree of porous materials concerning the so-called coefficient of effective permeability[15]. It is described by dependency (6):

$$K_{ef} = \sqrt{K_h K_v} \quad (6)$$

where: K_{ef} - coefficient of effective permeability, m^2; K_h - coefficient of horizontal permeability, m^2; K_v - coefficient of vertical permeability, m^2;

this coefficient characterizes average conditions resulting from gas permeability in the horizontal and vertical flow configuration.

The results for porous materials of this coefficient of anisotropy are shown in Fig. 4. Those results prove that the materials with the excessive fissuring such as coal chars in situ have a considerably anisotropic structure and a very good permeability. On the one hand, it proves that this group of coal chars is characterized by considerable fissuring but, on the other hand, it has a relatively large free area for the gas flow in comparison with the porous polyamide. On the other hand, the materials such as coke, natural pumice and coal char ex-situ belonging to the group of materials with moderate anisotropy have relatively limited permeability. The very opposing anisotropy is characteristic for synthetic pumice whose structure restricts gas flow conditions with the consequences above.

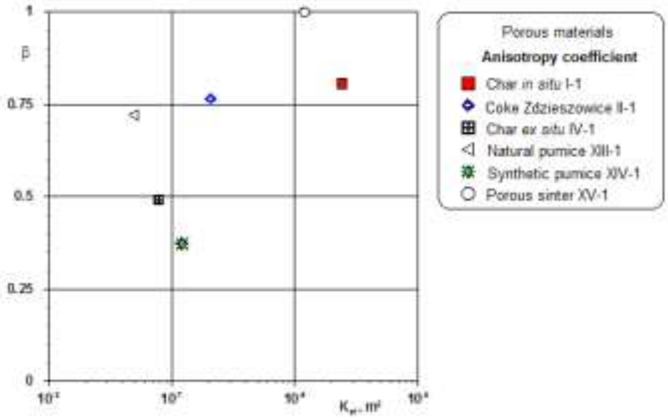

Figure 4: Coefficient of anisotropy of porous materials - average values

The distribution of experimental points shown in Fig. 4 proves that the scale of anisotropy of the porous materials may be very large, which depends on the material structure.

4. Conclusions

The recognition of the gas permeability problem of porous media has shown that there is very little information in the literature on the hydrodynamics of gas flow through solid (skeletal) porous materials. In this respect, appropriate experimental studies of gas permeability of such group of materials have been made, and hydrodynamic phenomena are resulting from gas flow pressure drop have been evaluated. These studies were supplemented with numerical calculations simulating the internal structure of the materials tested, taking into account the turbulence and spatial distribution of the flow channels.

It has been found that the scale of permeability of the porous skeleton materials is determined by characteristic parameters such as the degree of effective porosity for gas flow and also the anisotropic structure of these materials. Both these quantities have a considerable effect on the permeability coefficient, which was taken into account during the theoretical assessment of the issue. At the same time, the gas-permeability assessment of hydrodynamic parameters showed that none of the models available in the literature satisfies the correct correlation with the results of the experimental studies. This can be explained by the limited scope of these models to skeletal porous body characterized by significant anisotropy of the internal structure.

The research results on hydrodynamics of gas flow through frame-based porous deposits and the proved usefulness of the process assessment of that research may, in many cases, be practically used to immobilize of methanogenic microorganisms in adhesive deposits

5. Other recommendations

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