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International Journal of Current Research
Vol. 9, Issue, 12, pp.62010-62015, December, 2017

INTERNATIONAL JOURNAL
OF CURRENT RESEARCH

ISSN: 0975-833X

RESEARCH ARTICLE

INTERPRETATION OF GAS FLOW MECHANISMS IN ANISOTROPIC POROUS MATERIALS IN PHENOMENOLOGICAL TERMS

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ARTICLE INFO

Article History:
Received 18th September, 2017
Received in revised form
14th October, 2017
Accepted 07th November, 2017
Published online 25th December, 2017

Key words:
Porous material,
Gas flow,
Permeability mechanisms,
Anisotropy.

ABSTRACT

The mechanism of gas flow through porous materials and the selected models of the porous structure were analysed. As for the issue of gas flow through porous deposits that is basically discussed in this article, issues of the process were analysed through describing mechanisms of the gas flow in porous structures for the development of a new generation of clean energy sources, especially in the context of the production of biogas or syngas. This study discusses results of experiments on hydrodynamic assessment of gas flow through backbone (skeletal) porous materials with an anisotropic structure. The research was conducted upon materials of diversified petrographic characteristics, both natural origin (rocky) and process materials (char and coke). The study was conducted for a variety of hydrodynamic conditions, using air, as well as for nitrogen and carbon dioxide. The basis for assessing hydrodynamics of gas flow through porous material was a gas stream that results from the pressure forcing such flow. The results of measurements indicate a clear impact of the type of material on the gas permeability, and additionally – as a result of their anisotropic internal structure – to a significant effect of the flow direction on the value of gas stream. The results indicate the compliance of the used calculation method with the result of experiments.

Citation: Grzegorz Wałowski, 2017. "Interpretation of gas flow mechanisms in anisotropic porous materials in phenomenological terms", *International Journal of Current Research*, 9, (12), 62010-62015.

INTRODUCTION

A significant variety of porous deposits, both for their use in the industrial technology and their presence in the environment, makes the flow of liquids through this kind of materials tremendously complex and not finally recognised. At the same time, the reference books discusses this issue in a quire diverse way, as a greater emphasis is placed on the application of hydrodynamics of the flow of fluids through porous deposits (whether granular or frame-structured) than on basic research. As for the gas flow through porous deposits that is primarily discussed in this article, the process issues were analysed in category through describing mechanisms of gas flow in porous structures. Each porous medium has a specific porosity and its flow structure is subject to this porosity and to dimensions (diameter) and shapes of its channels at a given length of the channel. Another specific feature of porous bodies is their capability of storing and transporting liquids under the action of external and internal powers. Aksielrud and Altszuler (1987) argue that the gas flow through porous media whose channels (pores) have several millimetres or fewer is dominated by some process phenomena that emerge from the hydrodynamics of viscous liquid flow, whereas in case of the flows through structures whose pores are very small (tenths of micrometre), those phenomena are hampered by physical-chemical and diffusive mechanical effects that occur at the boundary of the phases. This fact is also proven by other authors (Dul'nev and Novikov, 1991; Mozhaev, 2002), but the diversity between those phenomena dissipates when gas keeps moving highly intensively. For the frame-structured porous materials such as coal and its coal chars, hydrodynamics that emerges during the flow is considerably affected by the structure of pores, powers and mechanisms of the gas flow. As an example, Fig. 1, following the authors of (Seewald and Klein, 1985), diagrammatically shows a porous structure of coal together with marked expected process mechanisms. Gas moves in micro-channels with a complex and tortuous shape, including the system of combined channels with a different geometry. Considering the combination level, gas contained in such porous medium may be classified into free gas filling pores and gaps, and gas that is physically and chemically combined with the medium through sorptive processes Fig. 2. The quantity of free gas is affected by the deposit porosity, the saturation of pores with gas, and the deposit pressure. On the other hand, the quantity of sorbed gas is, among others, subject to sorptive features of the porous medium, the temperature and the deposit pressure.

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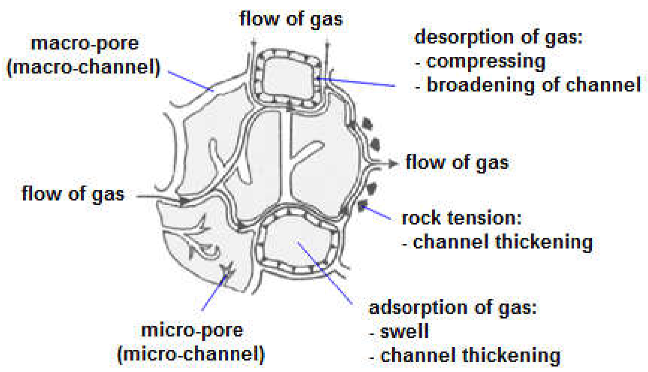

Fig. 1. Model of porous carbon structure, acc. (Seewald and Klein 1985)

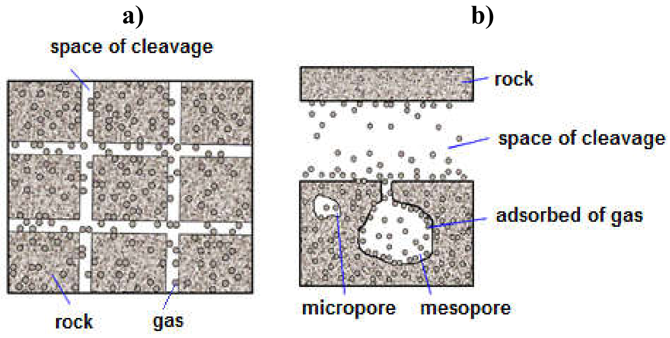

Fig. 2. Model of porous coal structure, acc. (Lin 2014): (a) deposit matrix, (b) matrix elements

The filtration transport of gas in the system of micro-pores with such structure entails the considerable modification of the porous pressure that affects the course of the gas diffusion (Topolnicki et al., 2004). In the in situ conditions the influence of the external pressure (rock mass) and the gas pressure may change the porous structure of the deposit. This results from the fact that carbon may be considered as a bi-porous structure in which micro-porous areas are compressed by a high pressure of liquids occurring in the pores (carbon dioxide, methane, water) and, in consequence, the geometry of the micropores changes or the micropores constrict in connection with the adsorption -absorption phenomenon; moreover, the structure of the medium considerably affects the deposit permeability. Generally, this system of the porous deposit may have a compact and uniform structure containing cracks and gaps, creating the so-called fractal flow system. Reich (1992) asserts that in such system there is an increase in the gas permeability, whereas Kovacek and Radke (1993, 1994), as well as Dyląg and Rosiński (2008) state that the fractal-based gas flow may be represented by a tree structure, according to Simons' model (Simons 1995). In this model, mezopores responsible for transport and storage are branches of micropores as illustrated in Fig. 3.

The outflow of gas from the so-called gap-porous medium reduces pressure in the deposit, which entails the change to the deposit permeability. On the other hand, the gas flow in natural fossil deposits is much more complex as it includes all the possible forms and mechanisms. This results from the fact in the process of release and flow of gas in the gap-porous medium there may simultaneously emerge such phases as the pressure reduction, diffusion and desorption, and inter-gap gas migration. It is noteworthy that desorption and filtration are closely correlated on a mechanical and energy basis (Seewald and Klein, 1985). The scale of the gas flow may also be affected by the velocity of desorption, irrespective of the deposit permeability (Krause and Treneczek 1996). As an example, Fig. 4, originating from Hagoort's study (Hagoort 1988), shows the models of gas movement resulting from the so-called rock matrix.

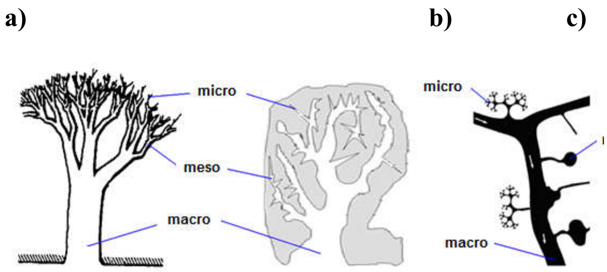

Fig. 3. Fractal flow system and functions of its tree structure: a) transfer, acc. (Simons 1995), b) storage, acc. (Niezgoda et al. 2012), c) transfer-storage, acc. (Fitzner 1993)

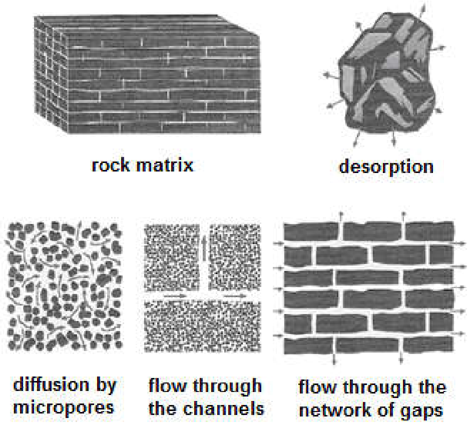

Fig. 4. Structural forms and gas flow models in the gap-porous medium, acc. (Hagoort 1988)

The reference books also describe statistical-physical models describing the course of the liquid flow process in porous structures, as illustrated in the studies (Dul'nev and Novikov 1991; Mid-Term 1999; Mozhaev 2002; Mozhaev 2004; Usowicz 2000). However, the occurring phenomena cannot be formulated as an explicit mathematical description. This is primarily caused by the considerable diversification of geometry and its changeability to the longitudinal shape of individual pores, the cross-section, the connections among individual channels involved in the gas flow, etc. In this context, our own research assesses conditions of hydrodynamics of the gas flow through backbone (skeletal) porous materials with an anisotropic structure. The results of research upon the assessment of gas permeability of various solid porous materials have been presented and the assessment of process conditions concerning hydrodynamics of the gas flow through materials with a diversified internal structure has been conducted.

Experiments

Scope and research methodology

To familiarise with hydrodynamic conditions of the gas flow through porous materials, detailed experimental tests were conducted to assess the gas permeability of porous materials with the diversified structure and, at the same time, the diversified process characteristics. The research material comprised various types of solid skeletal constructions, including those natural and those deriving from the thermal carbon gasification technology. Most of them were coal char in situ, coke, melted waste rock ex situ, and polyamide agglomerate of symmetrical spatial structure. All the types of materials applied in research underwent the assessment of selected parameters describing features characteristic for porous materials resulting from their porosity and physical structure as basic process quantities affecting the hydrodynamics of the gas flow through porous materials. The quantity-based assessment applied to such parameters as the apparent density and porosity of a specific type (sample) of the porous material. In this regard, structural research upon the tested porous materials conducted on the basis of the SEM scanning image (Wałowski, 2015) was helpful. The experiments pertained to two different measurement systems thoroughly analysed in other own works (Wałowski and Filipczak, 2012). The first system was used to assess the permeability of porous materials in the barbotage conditions. In this case, the shape of samples resulted from naturally obtained parts of the native material with an unspecified sample shape - Fig. 5a. The latter one was applied to analyse the permeability on the basis of the samples configured to the shape of the cubic solid - Fig. 6a. In this system the gas flow might be directed with respect to the arbitrarily selected X, Y and Z axes. This required the development of a special measurement system that is currently being patented by us (Wałowski et al., 2016). In their geometrical form those cubic-shaped samples were parts of volume samples and were compared with them with respect to their internal structure.

In both cases, the tests were conducted with reference to various gases (air, nitrogen, carbon dioxide) to the extent of the permeability stream resulting from the reference pressure. The permeability function of the pressure decline in the porous deposit was independently carried out, assuming the so-called multi-directional (fractal) system for the gas flow through samples with unspecified shapes (Fig. 5b) and the directional flow XYZ characteristic for cubic-shaped samples (Fig. 6b).

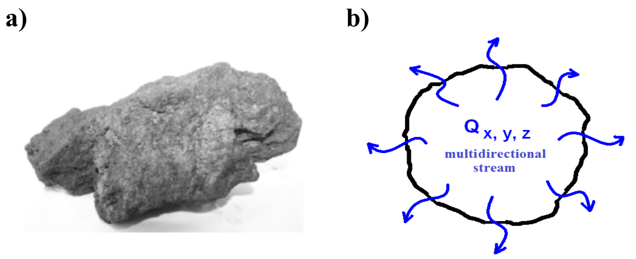

Fig. 5. Sample of unspecified shape, acc. (Wałowski and Filipczak 2016a): a) research material, b) flow chart (multi-directional - fractal flow)

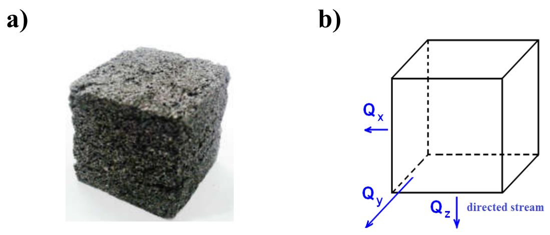

Fig. 6. Cubic-shaped sample, acc. (Wałowski and Filipczak 2016a): a) research material, b) flow chart (X,Y,Z-direction flow)

Research results and their analysis

The basis for assessing the hydrodynamics of the gas flow through deposits and porous materials is the characteristic of their permeability resulting from the pressure inducing this flow. In each case, this characteristic is determined by calculating the impact of the available overpressure on the obtained gas stream or vice versa - the impact of the gas stream on the value of this overpressure that corresponds to a decline in this stream pressure. In the latter case, this corresponds to the determination of complete resistances of the gas flow through such deposit. The results shown in Fig. 7 prove that with respect to porous materials in the form of coal char the nature of changes to gas permeability functions is highly diversified. For the same coal char in situ (I-1, I-2, I-3) there are obtained highly different permeability characteristics and their common deviation is expressly affected by the structure of the porous material. Moreover, those characteristics are parabolic, which proves their similarity to the hydrodynamics of the flow through the closed channels. On the other hand, the non-linear tendency of those characteristics proves the dominance of the turbulent flow, which is also associated with the deviation from Darcy's law (Wałowski and Filipczak 2016b).

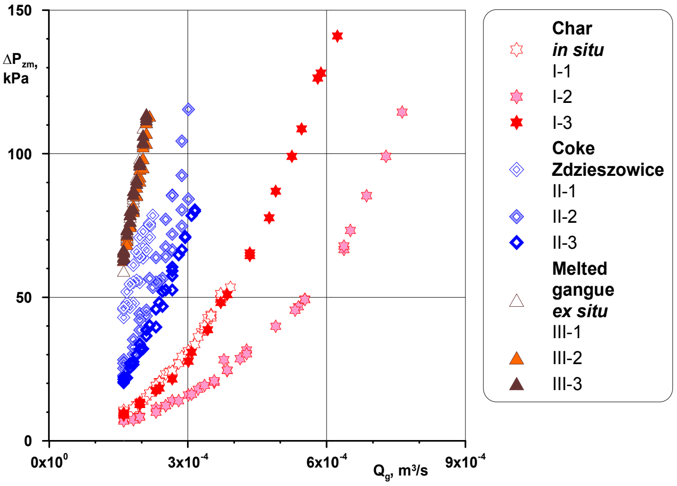

Fig. 7. Permeability of various kinds of porous materials - volume sample, acc. (Wałowski and Filipczak 2016a); I - coal char *in situ*, II – coke (Zdzieszowice), III – melted waste rock *ex situ*

The comparison to other materials as shown in Fig. 7 shows that coal char in situ (I-1, I-2, I-3) are porous structures which are much more permeable compared to coke (II-1, II-2, II-3) or melted waste rock (III-1, III-2, III-3). As for coke which has the highest porosity in this group this proves that a large part of its pores is closed for the gas flow and, concurrently, that the more complex structure of coal chars has characteristics of the gap medium, which at the same reference pressure ensures a much better gas permeability for this medium. On the other hand, in comparison with the aforesaid materials the permeability of the waste rock is undoubtedly justified by a relatively smaller porosity of this material and with the less participation of pores open for the flow (Wałowski, 2015). The analogous characteristics of permeability were made for the cubic-shaped samples (20x20x20 mm) by using the measurement system assessing permeability in the directional flow - Fig. 6. In this measurement, example results of measurements for coal char in situ and polyamide agglomerate are illustrated in Fig. 8 which shows characteristics of the air permeability in three independent flow directions (X, Y, Z).

The layout of experimental points shows that the permeability of coal char is considerably affected by the direction of the gas flow. This proves the explicit effect of the flow asymmetry with respect to the selected flow direction (axis) and, consequently, the explicit anisotropic structure of this type of material. On the other hand, for the porous polyamide that forms the agglomerate of spherical particles of identical dimensions (diameter of 0.1 mm), the permeability characteristics is not practically affected by the gas flow direction.

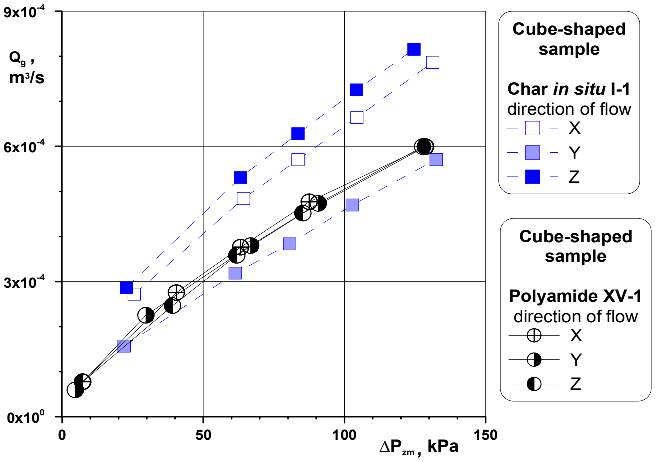

Fig. 8. Layout of experimental points characterising the asymmetry of the air flow with respect to three main axes of the cube (XYZ) for coal char and polyamide agglomerate, acc. (Wałowski and Filipczak 2016a)

At the same time, the determined characteristics prove that this porous polyamide, despite the fact its porosity is much smaller compared to coal char 30% (Wałowski, 2015), has similar characteristics of the gas flow. This proves the observation that the greater effect of the permeability of various kinds of coal char is rather the result of their porous and gap structure rather than the result of their porosity. It is interesting that the permeability characteristic of the porous polyamide is also of non-linear nature, which - with respect to the measurements - proves the advantage of the turbulent gas flow.

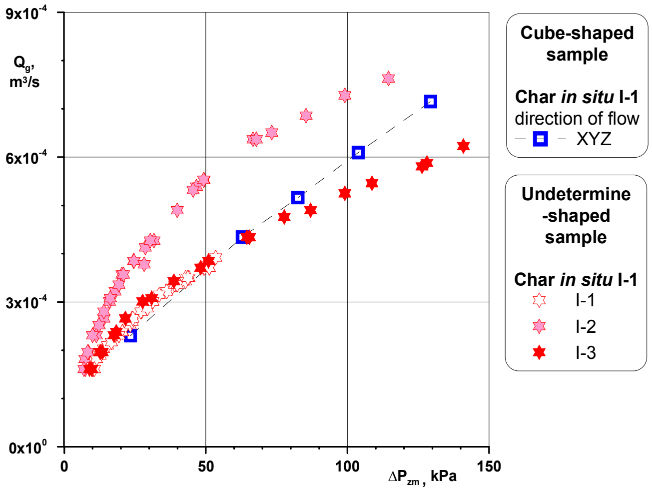

Fig. 9. Gas permeability of coal char for samples of various shapes, acc. (Wałowski and Filipczak, 2016a)

At the same time, the research results shown in Fig. 9 prove that the permeability of the porous material is not affected by the sample shape but by its internal structure. The layout of the experimental points shows that in the same conditions of the reference pressure between the volume coal char sample and the cubic-shaped sample (the figure shows averaged air flow values), the permeability characteristics of this material are of a similar nature and within the same scope of values.

The comparison of permeability characteristics of coal char in situ with respect to the flow of air, nitrogen and carbon dioxide is shown in Fig. 10 (those characteristics refer to cubic-shaped samples with dimensions of 20 x 20 x 20 mm). Regardless of the detected anisotropy of this material, it may also be observed here that to the entire extent of the reference pressure, the permeability of this coal char in situ is less for air than for nitrogen but considerably higher than for carbon dioxide. For this latter gas the limited permeability characteristics was also observed. Undoubtedly, this refers to the choking phenomenon that limits the permeability growth and increases the reference pressure.

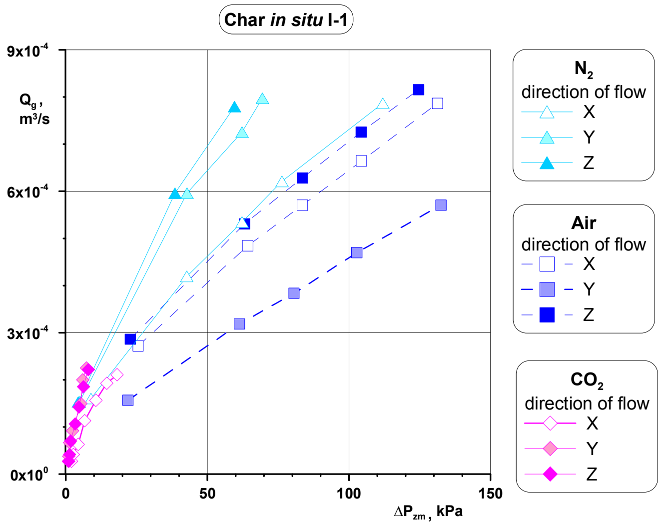

Fig. 10. Permeability of coal char in situ depending on a working medium, acc. (Wałowski and Filipczak 2016a)

This may be affected by the fact that the density is higher compared with the remaining ones but according to the fact proven in reference books (Michałowski and Wańkowicz, 1993) it is more reliable that the hyphenation choking effect expressed by a pressure decline in the porous material is greater, the greater resistance gas flowing the dense network of micro channels encounters - adiathermal conditions. On the other hand, other researchers (Klinkenberg, 1944; Blicharski and Smulski, 2012) suggest that this may be affected by the so-called Klinkenberg's effect (Wałowski and Filipczak, 2017) - a phenomenon that limits the movement of gas molecules with sizes of flow - pores channels. In the latter case, attention is drawn to the significance of this phenomenon, among others, in the aspect of the sequestration of carbon dioxide in geological porous deposits.

Summary

The theoretical assumptions resulting from the interpretation of the hydrodynamics of the gas flow through various media are formulated with greatly diversified models (mathematical and experimental), considering a straight-axial flow - Poissuille's laminar flow model (Darcy, 1856) - or a more complex filtration process, Darcy's model (Darcy, 1856) that is the only possible one for the laminar movement - or numerous modifications of those models for specific structural conditions of the deposit, based on the experimental criteria of the fluid movement in the closed spaces. The literature-based modifications such as the modifications made by Ergun (1952), Carman (1956), Forchheimer (Trykozko and Peszyńska, 2013), Windsperger (1991), most frequently refer to the determination of flow resistances, albeit they are dedicated for granular media or for their specific forms such as the infill of column apparatuses. A great difficulty for the application of the literature-based models and their adaptation to other (compared to their assumptions) process conditions is a result of a very diversified structure of porous materials, particularly the shape of pores, their cross-section, mutual connections that enable the liquid flow or the porosity size whose relatively high value does not always mean the greater efficiency of the frame-structured porous materials. The recognition of the issue of hydrodynamics of the gas flow through skeletal porous media shows that the reference books contain very little information. In this respect, relevant experiments on porous materials were conducted and hydrodynamic phenomena assessments resulting from gas flow resistances were carried out. The discussed research results concerning hydrodynamics of the gas flow through skeletal porous deposits may in many cases be used in process calculations of hydrodynamics of the gas flow through porous deposits, especially for the production of biogas in a monosubstituted reactor filled with adhesive deposits.

The study conducted as part of the project financed by the National Centre for Research and Development conducted in the BIOSTRATEG program, contract No BIOSTRAT EG1/269056/5/NCBR/2015 dated 11 August 2015.

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