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Research paper

Assessment of gas permeability coefficient of porous materials

Grzegorz Wałowski

Department of Renewable Energy Resources, Institute of Technology and Life Sciences, 67 Biskupińska Street, 60-463 Poznań, Poland

A R T I C L E I N F O

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A B S T R A C T

The results of experimental research upon the assessment of gas permeability of porous materials with respect to the gas flow. The conducted research applied to natural materials with an anisotropic gap-porous structure and - for comparative purposes - to model materials such as pumice and polyamide agglomerates. The research was conducted with the use of a special test stand that enables measuring the gas permeability with respect to three flow orientations compared with symmetric cubic-shaped samples. The research results show an explicit impact of the flow direction on the permeability of bio-char, which results from their anisotropic internal structures. The permeability coefficient of such materials was determined and an experimental evaluation of the value of this coefficient was conducted with respect to the gas stream and the total pressure drop across the porous deposit.

The process of gas permeability was considered in the category of hydrodynamics of gas flow through porous deposits. It is important to broaden the knowledge of gas hydrodynamics assessment in porous media so far unrecognised for the development of a new generation of clean energy sources, especially in the context of biogas or raw gas production.

1. Introduction

A large variety of porous deposits, both in terms of their use in the industrial technology, among others, leaching petroleum substances (Błaszczyk, 2014), cleaning the air from the volatile organic compounds (Iliuta & Larachi, 2005; Janecki, Gąszczak, & Bartelmus, 2016), bio-leaching black shale ores (Erust, Akcil, Gahan, Tusenuk, & Deveci, 2013; Barańska & Sadowski, 2015) and the occurrence in the natural environment - filtration (Darcy, 1856; Strzelecki, Kostecki, & Żak, 2008), movement of natural gases (e.g. methane) by rock masses (Krause, 2009), the flow of reaction gases from the thermal gasification in the georeactor (Gregg & Edgar, 1978; Smoliński, Stańczyk, Kapusta, & Howaniec, 2013) or retention in the process of underground bioconversion when selecting strains of microorganisms to achieve the maximum biogas efficiency (Stachowiak, Nowak, & Sztromwasser, 2011) makes the flow of fluids through this type of materials very complex and still not fully recognised. At the same time, the reference books are quite varied in its subject matter, where a greater emphasis is placed on the application of hydrodynamic of the fluid flow through porous deposits (whether granular or frame-structured) than on basic research.

Although the reference books widely analyse the gas flow through porous materials, they do not clearly interpret and explicitly indicate the nature of hydrodynamic phenomena accompanying this process. This mainly results from a very complex and diversified structure of porous materials which - due to changeable flow conditions - entails difficulties in interpreting those phenomena and - frequently due to the changeable process scale - from porous grains to porous deposits. And although the reference books do not lack models that consider structural features of porous materials in their descriptions, especially in the aspect of homogenisation theory (Auriault & Caillerie, 1989; Auriault & Royer, 1993; Auriault, Strzelecki, Bauer, & He, 1990; Łydżba, 1991, 2002), the impact of the anisotropic structure on the permeability of porous materials has not been sufficiently recognised. This situation becomes more complex with respect to the assessment of hydrodynamics of the gas flow through solid materials with porous (frame-structured) construction. At the same time, in this field it is difficult to find information on hydrodynamics of the gas flow through this type of porous materials.

In each case, the recognition of conditions of gas flow through porous deposits results in serious problems concerning the description of hydrodynamics and the evaluation of mechanisms of gas flow through those deposits, particularly due to their diversified construction and internal structure. On the other hand, by knowing those mechanisms, it is possible to evaluate process

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E-mail address: walowski.g@gmail.com.

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List of major signs

A	total cross-section of the flow channel (m^2)
F	cross-sectional area (m^2)
K	permeability coefficient (m^2)
L	flow path length describing the porous bad height (m)
Q	stream, volume flow rate (m^3/s)
d	diameter (m)
g	gravitational acceleration (m/s^2)
p	pressure (Pa)
u	apparent velocity (m/s)
β	parameter in this case indicates the deviation from the linear Darcy relationship, as caused by the additional kinetics effects ($1/m^2$)
ΔP	pressure drop (Pa)
ε	porosity
η	fluid viscosity (Pa·s)
ρ	density (kg/m^3)
ξ	coefficient of drag flow

Lower indices refer to

ASTM	acc. American Society for Testing and Materials
B	acc. Brinkman
D	acc. Darcy
Du	acc. Dullien
F	acc. Forchheimer
S	acc. Slichter
V	own model
X	direction
Y	direction
Z	direction
exp	measured
g	gas
o	apparent cross-sectional area or effective gas flow surface
ε	microchannel
0	ambient pressure

conditions that accompany hydrodynamics of gas flow through this type of materials, and, consequently, to thoroughly describe hydrodynamic conditions of gas flow through materials and porous deposits.

The assessment of gas permeability through porous deposits is significant for both process and technological reasons. In both cases, numerous attempts are made to search for effective methods for predicting permeability of porous materials, as well as effective ways of measuring and verifying the methods of this assessment. The methods used to measure gas permeability through porous deposits are very diversified in the literature, and it may be assumed that the only common feature of these methods is the structure of samplers, although there is no uniformly unified methods of this assessment. An additional difficulty in this regard is that the samples used in the research are of a different form and shape, and most often they are model deposits, which do not always correspond to the real conditions. A somewhat different aspect is that the assessment of gas permeability is generally carried out in one selected flow direction of the prepared sample, which in relation to porous natural materials leads to large quantitative errors. This state of affairs does not facilitate the transfer of measurement results to the real conditions, nor does it facilitate the establishment of clear criteria for the transfer of scale. This results in the individualisation of methods for assessing the gas permeability through porous deposits that are usually based on experimental formulas.

The examples included in the studies (Blicharski & Smulski, 2012; Darcy, 1856; Jansen, Meertens, & Wilms, 1964; Mertas, Sobolewski, & Różycki, 2013; Miura & Nishioka, 1992; Nomura et al., 2010; Popielski, 2000; RILEM Technical Recommendation, 1999; Roga & Wnękowska, 1952; Rozhkova, 2010; Shi, Xu, Shi, & Zhou, 2008; Tucker & Everitt, 1992, pp. 40–61; Śliwiński & Tracz, 2013) were used to characterise and analyse the selected methods for measuring the gas permeability through various porous materials with:

a) grain structure (soil, filter deposits);
b) frame structure (pumice, coal, coke and other coal chars);
c) capillary-porous structure (ceramic materials, concrete).

Virtually, in all the cases described in the literature there is no uniform view of the possibility of using in the gas flow hydrodynamics description the criteria for the assessment of gas permeability (gas flow stream). In addition, in the reference books there are considerable variations in the approach to the experimental assessment of the permeability parameters. It hinders to a great extent the possibility of the research results, which, consequently, leads to difficulties in adapting the existing computational models. An additional problem is the proper assessment of the nature of the flow and the actual flow parameters resulting from the structure of the porous deposit.

2. Materials and method

The permeability research was conducted upon a number of 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 solid frame structures thoroughly analysed in the study by Wałowski and Filipczak (2016a,b).

For selected types of porous material, a physical assessment of the structure of the tested materials was made. This was done on the basis of the available scanning image (SEM), as exemplified by the ex situ carbonisation sample shown in Fig. 1. To evaluate such a complete picture field, selected areas were selected to allow the graphical identification of the structure of the porous surface. For this purpose, specialized software for object-oriented image analysis was used, Iris-MediCom Wroclaw. In the example shown in Fig. 1, three such identification fields A, B and C are considered as representative of the cross-section. In each selected field (generally 1000 × 1000 μm), the free space circuit in a given plane is graphically displayed, both in the form of microchannels and slots. Using the graphical software tools, the total pore size and average size of each plot were determined for each designated area A, B, C, and on this basis the average porosity of each field analysed and average pore diameter were determined. Then, for each sample analysed in this way, mean values of these samples were determined - corresponding to this analysis, the sample results are presented in Table 1.

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