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Assessment of resistance of gas flow through porous materials in terms of the hydrodynamic model

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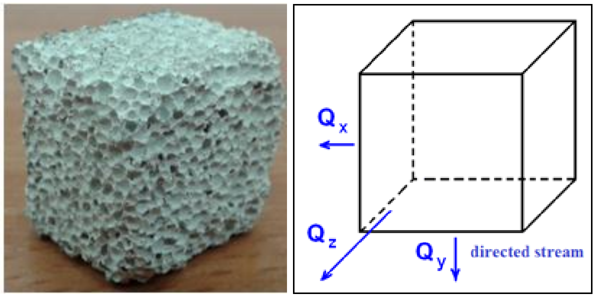
Abstract
The hydrodynamics of gas flow through porous materials and the selected hydrodynamic models of the porous structure were described. The literature-based conditions of the research on the description of hydrodynamics of the gas flow through porous structures were analysed. The process issues were discussed in the field of the "category of research with respect to selected methods for describing hydrodynamics of the gas flow through porous deposits". It is important to broaden the knowledge of gas hydrodynamics assessment in porous media so far unrecognized for the development of a new generation of clean energy sources, especially in the context of biogas or syngas production. The results of experimental research upon the assessment of the permeability of porous materials with respect to the gas flow. The suitability of calculation methods employed to calculate the hydrodynamics of the gas flow through porous materials was evaluated.

Keywords: hydrodynamics, porous structures, flow resistance

1. Introduction
In numerous industrial processes there is very often used the gas flow through various distributors of the phase contact surface, particularly liquid and gas phases. Those distributors most frequently create modules with a porous structure in the form of construction elements. The selection of a kind of such distributor and its internal structure considerably affects the hydrodynamics of the apparatus operation where such distributor is applied and is directly connected with the development of the inter-phase surface. The most common construction solutions of those distributors are symmetrical multi-channel structures designed for a specific purpose. Diameters of channels are adjusted on the basis of the volume gas flow to avoid excessively great local flow resistances [1, 2].
Another solution is slotting distributors whose variety is a system with a slot additionally filled with a porous material [3, 4]. In this last example the filling consists of materials with pores with dimensions of micrometres or of demister meshes with similar dimensions.
Another field of using porous structural materials are reaction catalytic combustion processes carried out in structural reactors [5, 6]. Most frequently, those reactors are associated with a group of monolithic reactors (so-called catalysts) equipped with ceramic cartridges with a multi-channel structure. The internal structure of those cartridges may be highly diversified and their common feature is that channels are highly packed and gas flows freely in a large free space, which, undoubtedly, is a great process advantage. In this case, metal monoliths are more rarely applied due to difficulties in placing a catalytic substance on their surface [5].
The process issue pertaining to the gas flow through porous deposits was considered as the review of research with respect to selected methods for describing hydrodynamics of the gas flow through porous deposits. It is important to broaden the knowledge of gas hydrodynamics assessment in porous media so far unrecognized for the development of a new generation of clean energy sources, especially in the context of biogas or raw gas production.

2. Materials and methods
The permeability research was conducted upon a number of diversified types of materials, the average porosity of which ranged from 45% to 88%. The research material comprised various types of solid frame structures: coal chars ex situ from the thermal processing of hard coal and there are also, natural and synthetic pumice - thoroughly analysed in the study by Wałowski and Filipczak [7].

2.1 Experimental stand
To obtain the research objective, the detailed experimental tests were conducted to assess gas permeability of porous materials with the diversified structure and the diversified process characteristics.
The research was conducted on a specially-designed stand [8], the fundamental component of which is the flow channel inside which the porous material sample is inserted, Fig. 4a.



(a) (b)

Fig 1: Sample of research material: a) porous material 20x20x20 mm – example natural pumice, b) flow diagram of the gas 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 [7]. 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 & Discussion

The reference books rarely refer to the flow of gas through porous deposits. They primarily focus on research and descriptions of phenomena that occur during the flow of gas through granular (loose), most frequently in the column filled with a porous material. Few studies refer to research upon permeability of gases through frame-structured porous materials. The reference books characteristic for those fields and referring to research upon hydrodynamics of gas flow through porous deposits are discussed in Table 1, whereas Fig. 1 shows the results of some research upon assessment of flow resistances through such deposits (adequate for the list included in Table 1) and includes relevant experimental data. The list contains only those studies that include research results or their data enables converting flow resistances at an apparent speed of gas (calculated for the full section of the column). For comparison, Table 1 also presents the results of own research.

Table 1: Studies relating to tests hydrodynamics of gas flow through a bed of granular and porous

Author	Characteristics of the deposit						Gas velocity w_o, m/s
	Type material	Height of the deposit *L*, m	Diameter of the column (deposit) *D*, m	Grain replacement diameter (pores) d_e, m	Sample cross Section *A*, m^2	Sample porosity (deposit) ε	
Palica *et al.* [9]	acidic peat	0.45	0.175	-	0.0240	0.47	0.07–0.16
	bark from deciduous trees					0.65	0.07–0.18
	peat for mushroom production					0.75	0.07–0.16
	wheat straw					0.93	0.05–0.16
	wood chips					0.68	0.05–0.15
	compost soil					0.62	0.05–0.15
	stalks from heather					0.93	0.06–0.16
Chmiel *et al.* [10]	Ecosorb-100	0.45	0.175	0.0005	0.0240	0.62	0.05–0.08
				0.0008		0.51	0.03–0.09
				0.0021		0.30	0.03–0.08
				0.0029		0.22	0.02–0.07
				0.0167		0.07	0.02–0.05
Łukaszuk *et al.* [11]	rape	0.95	0.196	0.00186	0.0121	0.40	0.05–0.20
	wheat			0.00410	0.0142	0.47	0.05–0.25
	corn			0.00785	0.0130	0.43	0.05–0.25
Kuśińska *et al.*[12]	wheat meal	10	0.196	0.004	0.0302	-	0.021–0.21
Wałowski (own research)	karbonizat (coal char) ex situ	0.02	-	0.000068	0.0004	0.45	0.03-0.11
	natural pumice			-		0.63	0.01-0.06
	synthetic pumice			-		0.88	0.02-0.18

Those results shown in Fig. 1 indicate very diversified computational characteristics of flow resistances as not only are they affected by a kind of deposit but also by the scope of permeability and the structure of a certain deposit and its porosity. This is also affected by the fact that various authors have different approaches to the process parameters resulting from the hydrodynamics of gas flow through porous deposits.

As for a phenomenological aspect the flow of liquid through the porous medium may be subject to various hydrodynamic criteria, which is affected by a medium structure, a kind of fluid (one- or multi-phase) and a flow forcing method (gravitational, pressure). A vast array of publications thoroughly analysed, among others, in studies by Strzelecki *et al.* [13], Piecuch [14], Orzechowski [15] and Błaszczyk [16] describing this issue on a research and analytical basis refer to the filtration process and they are generally identified with the laminar fluid flow through granular deposits according to Darcy's law [17]. It does not exhaust many other examples of the flow of fluids through porous media. For the turbulent flow of fluids the Forchheimer model [18] and the Ergun model [19] should be distinguished. The more advanced description of the flow through the spatial layout of capillaries in the form of the meandering channels is also included in the Kozeny-Carman model [20]. The reference books discuss other models of hydrodynamics of one- and multi-phase fluids flowing through porous media, considering the impact of fluid features and a kind of porous medium on the flow through granular deposits [14, 16].

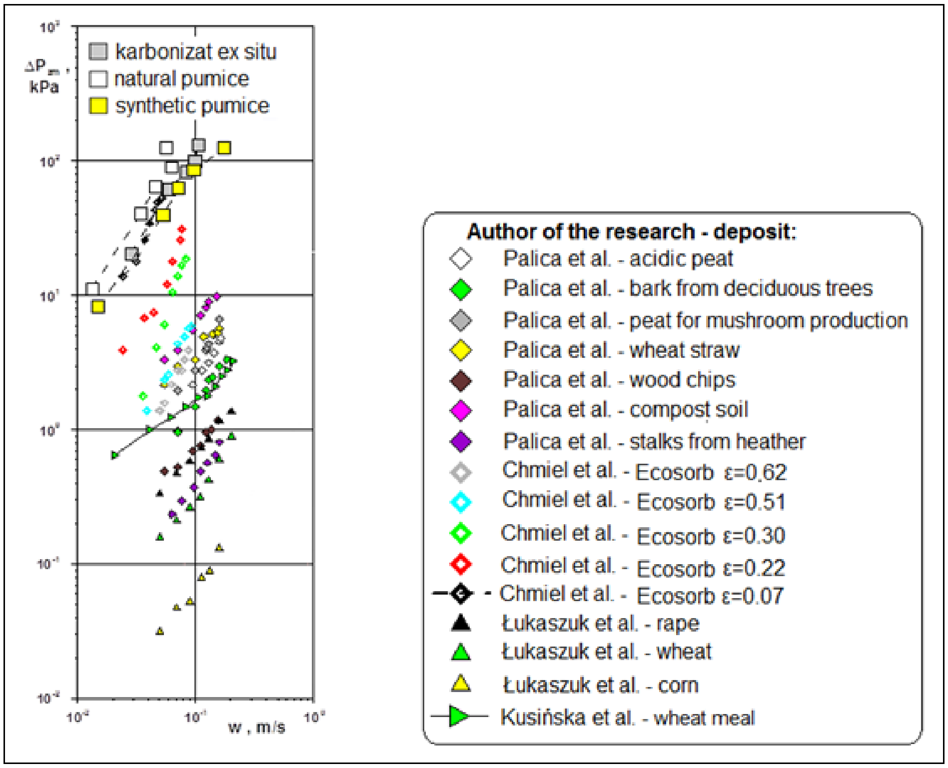


Fig 2: Summary of test results resistance of gas (ΔP_{zm}) flow through a bed of granular and porous (according to Table 1)

4. Conclusions

The process aspects referring to the hydrodynamics of gas flow through porous deposits are basically analysed in the literature for two structures with different deposit configurations. The first structures (analysed in most number of studies) are granular media where the liquid flows in the free space between grains of the material and in this case it may be observed that the whole porous space is an active space for this flow. The latter structure constituting solid porous materials is characteristic by a frame-structured construction, the structure of which determines the conditions and nature of the flow of liquids. In those frame-structured structures the flow only occurs inside pores and channels that affect the structure of the material, the flow is only limited to mutually-connected open channels and pores (some pores may be closed or blind). In both cases it is difficult to describe the hydrodynamics of gas flow in porous media not only due to the liquid movement in porous materials but also due to their unique structure.

In the context of the article-analysed conditions of the gas flow through frame-structured porous materials it should be stated that (i) mechanisms arising from the hydrodynamics of gas flows in porous deposits are described differently but the basis for assessing hydrodynamics is generally models based on the interpretation of Darcy's law [21]; (ii) due to various mechanisms and forms of gas transport in porous deposits (among others laminar or turbulent flow, diffusion, Knudsen's transport [22]) that, in most cases, occur simultaneously, the correct interpretation of hydrodynamic processes is a very complex problem that is frequently difficult to be described unambiguously; (iii) theoretical considerations arising from the interpretation of hydrodynamics of gas flow through porous media are described by highly diversified models, both mathematical and experimental, considering the straight-axial flow (as in Poissuille's laminar flow model [22]) or a more complex filtration process (according to Darcy's model and the only possible for the laminar flow) and numerous modifications of those models for specific structural conditions of the deposit based on experimental criteria of the liquid flow in closed spaces; the literature-based modifications (among others Ergun [19], Carman [20], Forchheimer [23], Windspergera [24]) most frequently refer to the determination of flow resistances, despite the fact they are designed for granular media or their specific form - the filling of column apparatuses; (iv) great difficulties in applying the literature-based models and their adaptions to other process conditions compared to the assumptions of those models are associated with a highly diversified structure of porous materials, especially in the context of the shape of pores, their cross-section, mutual connections that enable the liquid flow or the porosity whose relatively high value does not always prove the greater capacity of the frame-structured materials.

As part of the strategic project entitled: "Interdisciplinary research upon the improvement of energy efficiency and an increase in the share of renewable energy sources in the balance energy of the Polish agriculture" conducted within the BIOSTRATEG 1 programme with acronyms BIOGAZ and EE at the Institute of Technology and Life Sciences, the Department of Renewable Energy Resources in Poznan, there was, among others, an attempt to develop the model of the hydrodynamics of the gas flow in porous deposits.

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