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Hydrodynamics of gas flow through anisotropic porous materials in phenomenological and numerical terms

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Abstract 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 – cokes. The study was conducted for a variety of hydrodynamic conditions, using air. 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. In aspect of scale transfer problem, a method of mapping the flow geometry of skeletal materials has been developed and usefulness of numerical methods has been evaluated to determine pressure drop and velocity distribution of gas flow. The results indicate the compliance of the used calculation method with the result of experiments.

Keywords: Biochar; Coke; CFD; Permeability

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Nomenclature

A – cross-section area, m^2
L – column height (deposits), m
K – permeability coefficient, m^2
Q – volume flow rate, m^3/s
P – pressure, Pa
Re – Reynolds number
a – specific surface area, $\mathrm{m}^2/\mathrm{m}^3$
b – side of cube (edge of cube), m
c – constant
d – diameter, m
f – function
g – mass velocity, $\mathrm{kg}/(\mathrm{m}^2\mathrm{s})$
w – velocity, m/s

Greek symbols

Δ – difference (decrease)
β – Forchheimer calculation coefficient (inertia parameter)
ε – deposit porosity, $\mathrm{m}^3/\mathrm{m}^3$
η – dynamic viscosity coefficient, $\mathrm{Pa}\,s$
φ – coefficient of filling shape
λ – coefficient of flow frictional resistance
ρ – density, kg/m^3
ξ – modified coefficient of flow resistances

Subscripts

b – absolute value
e – equivalent dimension (substitute)
f – fluid
g – gas
k – capillary
o – value calculated on the total deposit section (apparent value)
p – spherical particles
zm – measured value
ε – value calculated relative to porosity

1 Introduction

The reference books frequently discuss other models of hydrodynamics of single- and multiphase fluids flowing through porous media, considering the impact of fluid features and a kind of porous medium on the flow through granular deposits [1–4]. However, the vast majority of those models pertain to granular deposits but only a few studies analyse gas permeability through backbone (skeletal) porous materials. An exemplary comparison of literature [5–12] referring to hydrodynamics of gas flow through selected porous beds is characterized in Tab. 1.

The assessment of flow resistances is most frequently based on the analogy with the flow through closed channels according to the Darcy-Weisbach [13,14] equation

$$\Delta P = \lambda_\varepsilon \frac{\rho_f w_\varepsilon^2}{2} \frac{L}{d_\varepsilon} \ . \tag{1}$$

The flow resistance factor as a function of Reynolds number is described by the following dependence:

$$\lambda_\varepsilon = f(\mathrm{Re}) = c\mathrm{Re}^{n-2} \ , \tag{2}$$

where the Reynolds number is defined as

$$\mathrm{Re} = \frac{w_\varepsilon d_\varepsilon \rho_f}{\eta_f} \ . \tag{3}$$

A different method was developed by Ergun [5] whose model is based on the experimentally determined flow resistance factor according to the equation

$$\lambda_f = \frac{150}{\mathrm{Re}} + 1.75 \ . \tag{4}$$

This equation fully characterises the hydrodynamics of the liquid flow through the porous deposit with respect to the laminar and turbulent flows [15], at a value of the Reynolds number in the following form:

$$\mathrm{Re} = \frac{w_o d_e \rho_f}{(1-\varepsilon)\eta_f} \ . \tag{5}$$

The dependence (4) shows that with respect to the laminar flow when the Reynolds number has very small values ($\mathrm{Re} < 10$), the factor element responsible for friction flow resistances has frequently a greater value compared to the developed turbulent flow ($\mathrm{Re} > 10^3$) when the value slightly differs from the constant of the equation.

A similar solution recognising the parameters for the laminar flow is provided by Brauer [6] :

$$\frac{\Delta P}{L} = 18\varphi_\varepsilon \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\eta_f w_o}{d_e^2} = \lambda_f \mathrm{Re} \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\eta_f w_o}{d_e^2} \ , \tag{6}$$

where the flow resistance factor at $\varphi_\varepsilon = k/2$ is described with the dependence

$$\lambda_f = \frac{18\varphi_\varepsilon}{\mathrm{Re}} \, . \tag{7}$$

The research results show that a Brauer's model-based calculation range may also be extended to the turbulent flow [16] at the flow resistance factor by using the following relation

$$\lambda_f = \frac{160}{\mathrm{Re}} + \frac{3.1}{\mathrm{Re}^{0.1}} \, . \tag{8}$$

In the particular case of spherical grains with a diameter of particles d_p for which the specific area is determined with the formula

$$a = \frac{6}{d_p} \tag{9}$$

this substitute diameter is determined with the formula

$$d_e = \frac{2}{3} d_p \frac{\varepsilon}{1-\varepsilon} \, . \tag{10}$$

Therefore, in case of deposits with a regular and repetitive shape, the determination of the substitute diameter d_e and its specific area a is not, generally, difficult and is possible on the basis of the already known geometrical dimensions of the deposit. However, for deposits comprising polydisperse elements with a various grading and shape, the determination of those values frequently requires to carry out very tedious statistical research.

Generally, it may be assumed that the non-linear dependence between the pressure decrease and the liquid flow is characteristic for a great amount of inertia forces that are significantly higher than the impact of viscosity forces. The model that is directly used to describe those conditions is an empirical Forchheimer equation [17,18]

$$\rho_f \frac{\Delta P}{L} = \frac{\eta_f}{K} g_o + \beta g_o^2 \tag{11}$$

and at $g_o = \rho_f w_o$

$$\frac{\Delta P}{L} = \frac{\eta_f}{K} w_o + \beta \rho_f w_o^2 \, . \tag{12}$$

Among other experiments, it is also worth emphasising those experiments that directly refer to the gas flow in deposits with various configurations.

Skotniczy [7] carried out a series of experiments involving the determination of resistances of the gas flow in the soil as a porous medium with the exchange of heat (those experiments involved the flow of air through ground heat exchangers). He showed that the measurement data were within the range of the applicability of Darcy's law, which corresponds to the conditions of the laminar flow. Skotniczy concluded that if flow resistances and porous velocity (measured values) were known, values of the permeability factor would be quite precisely estimated.

Warpechowski and Jopkiewicz [8] analysed hydrodynamics of the gas flow in the coke deposit and proved that the estimated values of the Reynolds number exceeded 3000 and the value of the resistance factor is much more affected by geometrical parameters of the deposit than the change to the gas viscosity.

By analysing the combustion process in the granular deposit Hehlmann *et al.* [9] observed that calculation equations based on the capillary model of the layer gave results that considerably differed from the experimental data [19–22]. Those authors show that better results are obtained on the basis of energy model based on characteristic parameters of the deposit with variable flow parameters coincident with the filtration process parameters. As a result, they formulate a correlation equation that describe resistances of the gas flow through the granular deposit, which, however, only applies to a selected process issue.

On the other hand, researchers from the Institute for Chemical Processing of Coal [10] emphasise that in case of the temperature plasticisation of the crashed coal loosely placed in the industrial coke chamber, gas is primarily emitted inside the plastic layer and considerably affects the pressure generated in the deposit. The obtained results of research on changes to the gas pressure show that a plastic coal layer that is formed as a result of the coal coking (carbonization) process is significantly resistant to the flow of the emitted gas. Once the plastic layer is transformed into semi-coke, in the deposit there begins to dominate channel structures (cracks) through which gas may, without any significant resistance, flow in the entire deposit. According to the research authors [10], in the conditions of this process the gas permeability factor may be determined according to Darcy's law.

It is interesting that, as emphasized by the authors of the study [11], the Darcy-Forchheimer model may be adapted to the description of hydrodynamic phenomena in the gas flow through the so-called constant metal foams that most frequently form symmetrical cell structures. The research of those authors showed that the use of the Forchheimer correlation in the form of Eqs. (11) and (12) reasonably well gives the conditions of the flow through this type of structures and this fact is also proved in the one- and two-phase flow with the use of gas and liquid.

Table 1: Selected studies referring to research upon hydrodynamics of gas flow through granular and porous deposits.

Author	Type of gas	Deposit characteristics				
		Type of material	Deposit height H, m	Diameter of column /deposit d, m	Equivalent diameter of grain/ pores d_e, m	Porosity of sample /deposit ε
Ergun [5]	CO_2, N_2, CH_4, H_2	coke	0.95	0.724	–	0.42
Brauer [6]	air	formed spheres of uniform size	0.50	–	0.0024	0.32
Skotniczy [7]	air	glass balls	0.04	0.110	0.0050	–
Warpechowski, Jopkiewicz [8]	air	coke	0.95	0.380	0.0330	0.42
Hehlmann [9]	air	fine coke	0.20	–	0.0049	0.61
Mertas *et al.* [10]	N_2	coke yielded grains	0.08	0.020	–	–
Dyga, Płaczek [11]	air	aluminium foam, 20PPI	1.00	0.020	0.00345	0.93
Wong *et al.* [12]	air	biochar with clay	0.07	0.070	3×10^{-6}	0.1

Wong *et al.* [12] have shown that the effects of biochar content on biochar-amended clay (BAC) gas permeability is highly dependent on the degrees of compactions (DOC). At high DOC (90%), the gas permeability of BAC decreases with increasing biochar content due to the combined effect of the clay aggregation and the inhibition of biochar in the gas flow. However, at low DOC (80%), biochar incorporation has no effects on gas permeability because it no longer acts as a filling material to the retarded gas flow. The results from the present study imply that compacted BAC can be used as an alternative final cover material with decreased gas permeability when compared with clay.

Those examples show that models characterising the hydrodynamics of the liquid flow in porous media are highly diversified with respect to their merits and for real flow conditions it is very difficult to unequivocally indicate the usefulness of individual models for specific process and technological conditions. This leads to the conclusion that in each case it is necessary to experimentally verify the scope of applicability of those models in process calculations.

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 one type 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. In the aspect of the phenomenological assessment of hydrodynamic phenomena an attempt was made to map by means of the numerical flow geometry of backbone (skeletal) materials and there was the assessment of suitability of the numerical modelling of hydrodynamics of the gas flow through backbone (skeletal) porous materials.

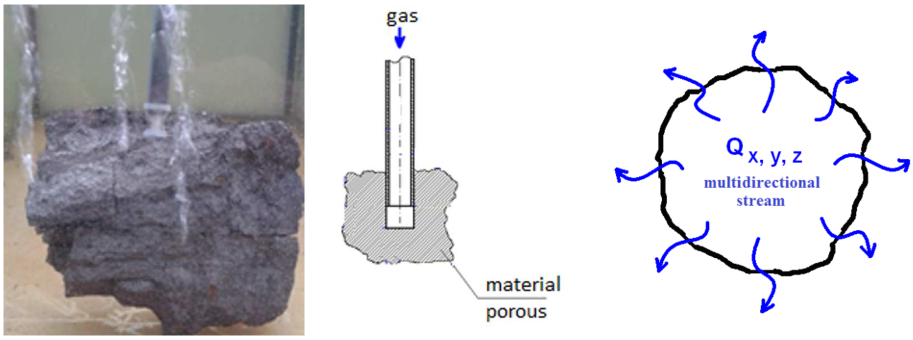
2 Experiments

2.1 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 one types of solid skeletal constructions those deriving from the thermal carbon coal coking (carbonization) technology – coke.

One the type 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 snanning electron microscope image [4] was helpful.

The experiments pertained to two different measurement systems thoroughly analysed in other own works [23,24]. The first system (Fig. 1a) 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. 1b.



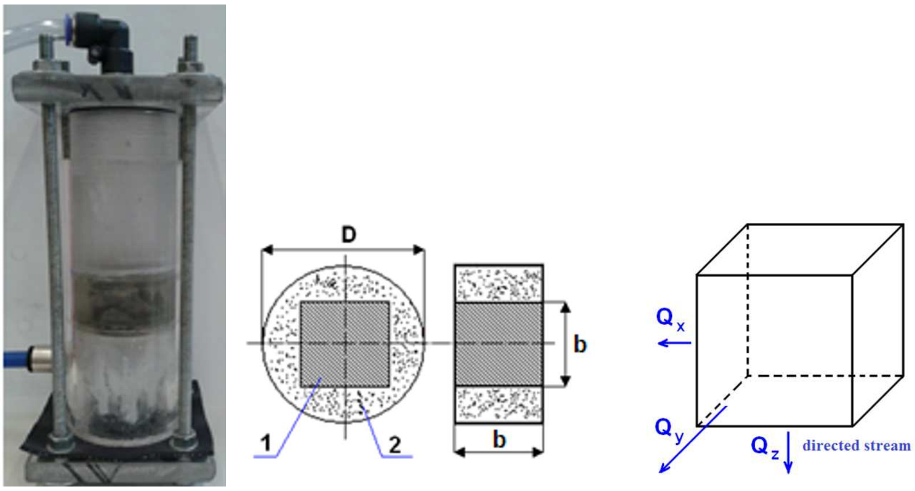
a) b) c)

Figure 1: Research material (multi-directional – fractal flow): a) fragment of system – view, b) diagram of a measurement method, c) flow chart.

The latter one (Fig. 2a) was applied to analyse the permeability on the basis of the samples configured to the shape of the cubic solid – Fig. 2b. In this system the gas flow might be directed with respect to the arbitrarily selected X, Y, and Z axes. In their geometrical form those cubic-shaped samples were parts of volume samples and were compared with them with respect to their internal structure.

This required the development of a special measurement system that is currently being patented by us [25]. This specially designed permeability meter tests the permeability of cubic-shaped samples towards any direction of its axis, which is possible by applying a special sealing system to the measuring cell that enables the measuring of permeability in any direction (X, Y, Z) of the location of the sample in the system. The scheme of this measurement cell together with the marking of the sealing material and the measurement sample is shown in Fig. 2b.

In both cases, the tests were conducted with reference to gas (air) 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. 1c) and the directional flow XYZ characteristic for cubic-shaped samples (Fig. 2c).



a) b) c)

Figure 2: Research material (X,Y,Z – direction flow): a) fragment of system – view; b) scheme of measurement cell: 1 – porous materia (cubic sample) l, 2 – sealing material; $D = 49$ mm, $b = 20$ mm; c) flow chart.

2.2 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. As for coke (Fig. 3) which has the absolute porosity ($\varepsilon_b = 54.3\%$) this proves that a large part of its pores is closed for the gas flow [4].

The analogous characteristics of permeability were made for the cubic-shaped samples ($20 \times 20 \times 20$ mm^3) by using the measurement system assessing permeability in the directional flow – Fig. 2.

The hydrodynamic results obtained from the permeability of porous materials not only affect the assessment of the stream of the gas flow through those materials but they also refer to the loss of pressure energy in that

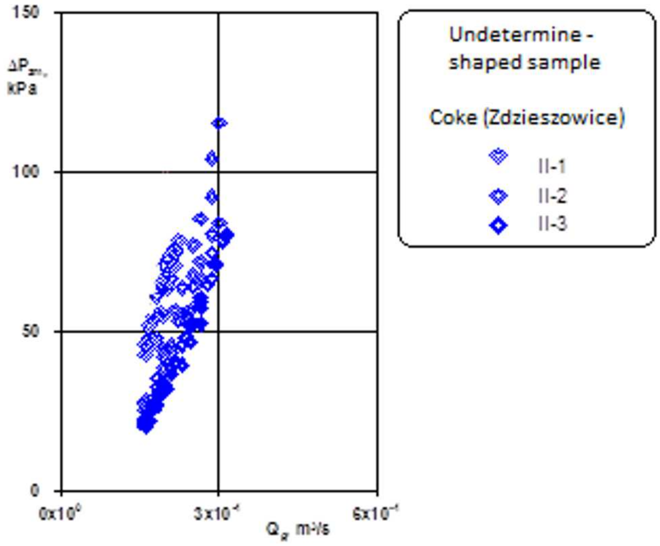


Figure 3: Permeability of porous materials (volume sample): II Ő coke (Coking Zdzieszowice).

flow. The direct measure of that loss is flow resistances that may be interpreted differently in the detailed quantitative assessment, the selected examples of which are included in the introduction section. These examples also show that for the conditions considered in their own experiments, used for comparative analysis of the model equations listed above, they do not fulfil the description of hydrodynamics of gas flow through porous materials that are subject to own research [4]. This is caused by the great complexity of hydrodynamic phenomena for the gas flow through frame-structured porous materials and by a limited number of computational models and methods characteristic for the hydrodynamics of liquid flow in the closed structures.

One of those possibilities is to include in the hydrodynamics description the conditions resulting from the energy dissipation that occurs during the movement of gas in porous and capillary spaces of porous materials. From the experimental view point, this phenomena may be associated with a certain alternative (equivalent) coefficient of resistance that includes conditions resulting from the coefficient of friction between liquid and walls of flow channels and from the pressure reduction caused by the disturbance to the velocity profile characteristic for stream choking. In such presented issue, the total resistance of gas flow through the porous deposit may be identified with the general dependency

$$\Delta P = \xi \frac{\rho\, w^2}{2} \, . \tag{13}$$

considering the relevant adjustment of flow parameters of the porous structure. This approach is justified by the fact that in the structure of flow microchannels a share of friction in the flow resistance is marginal.

When directly using the Weisbach equation (13) it needs to be directly adapted to the porous structure, for which this relation may be as follows:

$$\Delta P = \xi_\varepsilon \frac{\rho_g w_\varepsilon^2}{2} \, . \tag{14}$$

In this case, the flow velocity

$$w_\varepsilon = \frac{Q_g}{A_\varepsilon} = \frac{Q_g}{\varepsilon\, A_o} \tag{15}$$

refers to the section resulting from the average area of the deposit A_ε open for this flow and resulting from the porosity of the deposit ε and its complete section A_o. For such interpreted conditions Eq.(14) may be used to experimentally determine a value of the coefficient of flow resistance as its certain equivalent value ξ_ε, (16) that cumulatively consider all the mechanisms resulting from the hydrodynamics of the gas flow through porous materials

$$\xi_\varepsilon = \frac{2}{\rho_g\, w_\varepsilon^2} \Delta P_{zm} \, . \tag{16}$$

Some examples of the results of such coefficient of flow resistance are shown in Fig. 4 The reference of the value of this coefficient to the Reynolds number was used in this respect Here, at a gas speed of w_o resulting from the diameter d of the supplying nozzle (Fig. 1b), the Reynols number is determined as

$$\mathrm{Re} = \frac{w_o\, d\, \rho_g}{\eta} \, . \tag{17}$$

Those results show the decrease in changes to the value of the resistance coefficient as a result of increase in the Reynolds number, which complies with the physics of the analysed phenomena and the scale of those changes is sometimes extensive. This proves that the flow resistances are highly affected by the dynamics of gas flow through porous materials, in particular by disturbances of the velocity profile.

Coke is characterized by a developed system of microporous channels and gaps, showing relatively much greater resistance to flow (Fig. 4). This is undoubtedly caused by the fact that a large part of these microchannels is in this case closed (II-1) to the flow or simply closed (II-2, II-3).

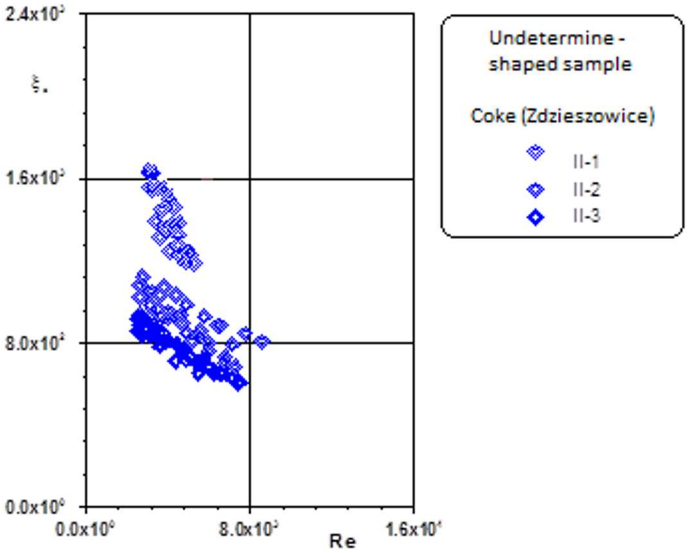


Figure 4: Substitute coefficient of gas flow resistance for coke (volume sample): II – coke (Zdzieszowice).

At the same time, the research results shown in Fig. 5 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 coke 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 range of values.

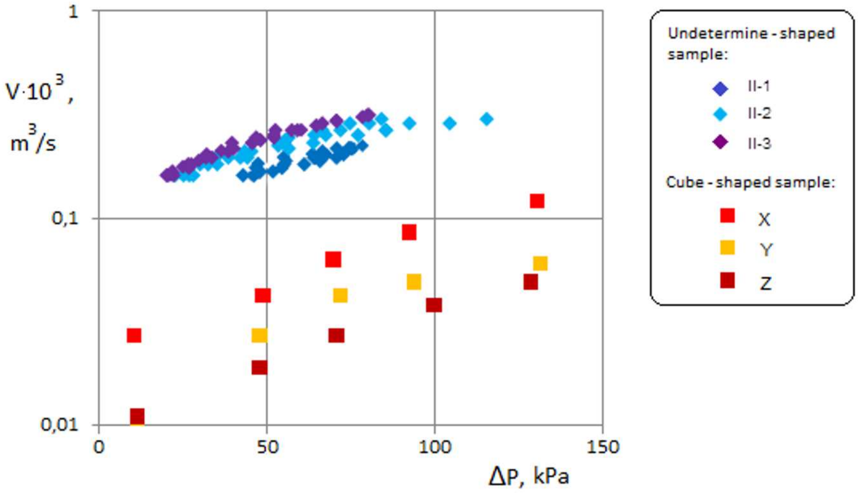


Figure 5: Gas permeability of coke for samples of various shapes: II – coke (Zdzieszowice).

3 Assessment of hydrodynamics in the aspect of numerical model research

3.1 Multiscale issue

Considering the porous medium features resulting from homogenisation and its phenomenological image, the scale transfer concept is based on the numerical modelling by using the structural scale transfer model based on the real (experimental) image of the porous material image as shown in Fig. 6. This concept transfers the scale of any shape of the porous deposit to the cubic shape (Fig. 6a) comprising fundamental particles of an internal structure resulting from the actual hydrodynamic characteristics of the analysed porous material (Fig. 6b).

It is also noteworthy that currently the alternative way of analysing the multiscale issue are the methods (still improved) based on numerical simulations of fluid transport in porous systems, supported by the computed microtomography [26]. In this case, two methods are predominant, viz. *pore network method* [27] and *lattice Boltzmann method* [28].

Our own concept considers the circumstances of the multiscale issue resulting from both methods, which is an innovative perspective on the problem of transferring the scale of hydrodynamics of the gas flow in the porous deposit.

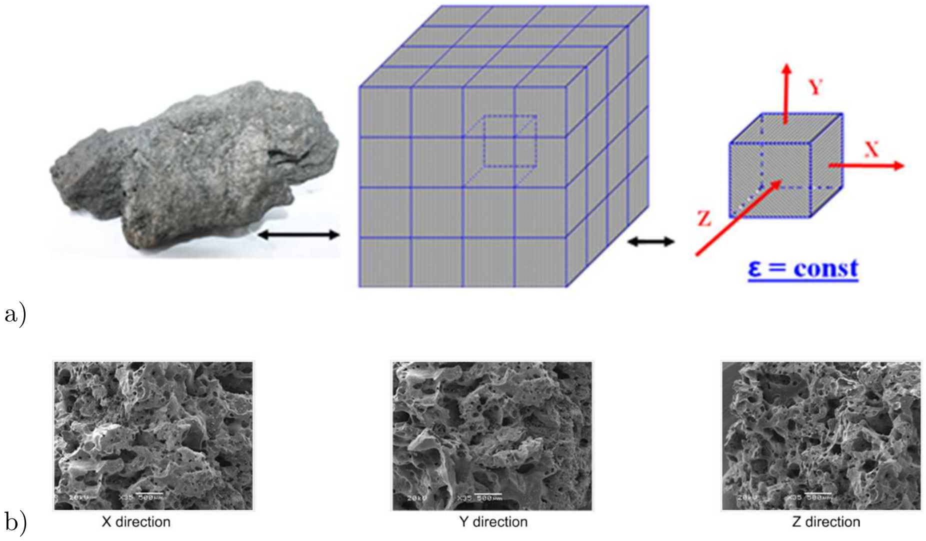


Figure 6: Concept of the scale transfer for samples with various geometry: a) characteristics of process parameters (ε – porosity), b) elementary structure.

4 Numerical analysis results

For the purposes of modelling hydrodynamics of the gas flow through the skeletal porous material, there was prepared a relevant simulation algorithm by means of the commercial Ansys Workbench programme (using the so-called *geometry*, *mesh*, and *fluent* computational blocks), the details of which are included in our own studies [4,29].

The basis for this modelling is an original methodology of creating the quasi-fractal geometry of the network of meandering microchannels that enables determining the surface criteria of the solid – Fig. 7. This enables modelling the geometry of the skeletal porous deposit (Fig. 8) for the quasi-fractal network and the processing of further calculations in compliance with adequate numerical methods concerning the assessment of hydrodynamics of the gas flow through porous materials. In consequence, numerical simulations make it possible to obtain the image of the distribution of pressure and speed of the gas flow which is shown for a selected field in Fig. 9 ($b = 20$ mm, $d_k = 123$ μm, $\varepsilon_b = 54.3\%$). It was therefore concluded that the turbulence of the gas flow in the skeletal structure, depending on the cross-section of the flow, occurs for the combined microchannels as shown in Fig. 9b.

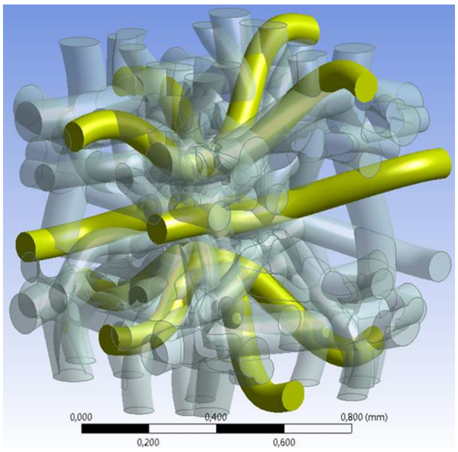


Figure 7: Geometry of micro-channel network.

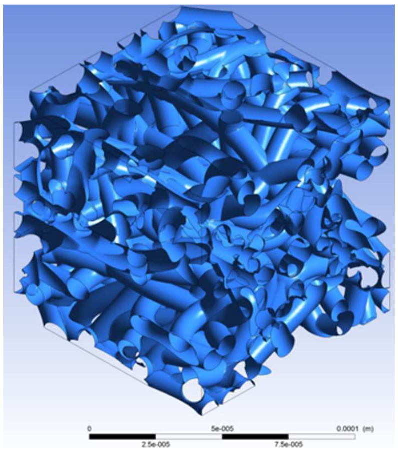
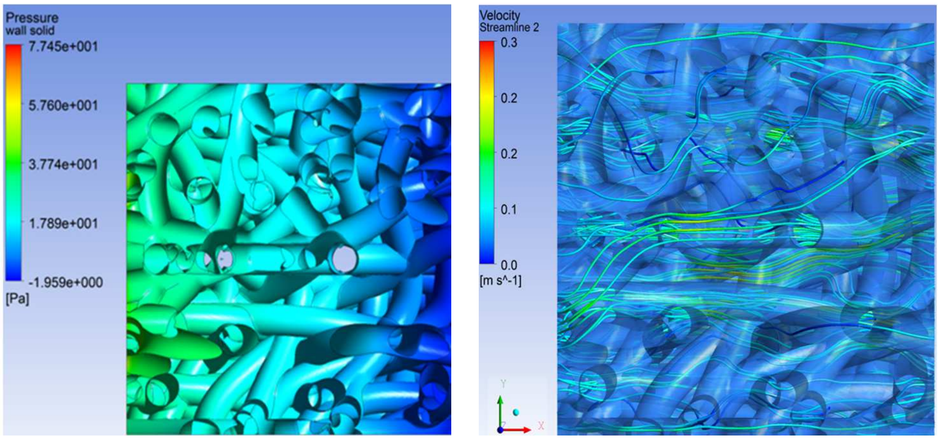


Figure 8: Geometry of skeletal structure.



a)

b)

Figure 9: Gas flow in the skeletal structure: a) pressure field, b) speed lines.

Examples of numerical calculations concerning speed of the gas flow with respect to the reference pressure are shown in Fig. 10. Those results refer to the sample of coke with the following parameters (average values): absolute porosity $\varepsilon_b = 54.3\%$, substitute diameter of pores $d_k = 123.4$ μm, substitute volume of any shape sample 0.09 m^3, at the so-called unit times of the volume of the cubic sample with respect to the total volume of any shape sample about 11.8 (Fig. 6).

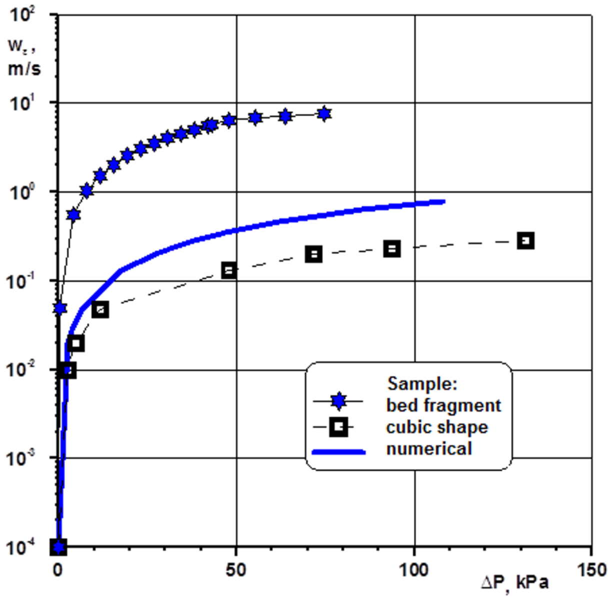


Figure 10: List of experimental and numerical results for coke.

The layout of experimental points and the course of numerical characteristics prove that the adopted calculation methodology reliably characterises the conditions resulting from hydrodynamics of the gas flow through porous deposits. The tendency of changes in the permeability function – for a specific network geometry in the graph is shown by the gas flow speed – which is repeatable and slightly differs from the experimental values.

The obtained results prove the correctness of the adopted calculative methodology and enable assessing hydrodynamics of the gas flow in porous structures of coke within the wide scope of process parameters. This may be an important contribution to the validation of the research results in conditions of actual porous deposits.

The expected (average) value for the adopted measurement is 3.74×10^{-4} m^3/s, at the result (at the confidence level 0.99) $3.74 \times 10^{-4} \pm 3.29 \times 10^{-5}$ m^3/s, which gives an average measurement error for the analyzed series 8.7%. The average relative error for the entire gas flow range was ±5.3%.

5 Summary

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. Those experiments were supplemented by numerical calculations simulating the internal structure of the tested materials, considering the integrated area of the quasi-fractal multilayer network. It has been proven that on the basis of the experimental research it is possible to develop a methodology necessary to transfer the scale for hydrodynamics of gas flow through porous deposits and their validation by numerical methods.

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.

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