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FILTRATION OF DESORBING GAS IN A BIDISPERSE POROUS LAYER

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Abstract. The relevance of considering filtration problems taking into account adsorption-desorption processes is associated with the safety of mining and coal developments in the presence of adsorbed gas deposits in the rock, as well as when solving environmental problems, in particular, the storage of greenhouse gases in soils and coal seams.

In this work, according to modern concepts, the porous medium is presented in the form of two types of pore channels, hydrodynamically connected to each other, but very different from each other in their characteristic diameters. It is also accepted that the surfaces of both types of channels are covered with a solid deposit of adsorbed gas, which begins to be released when the pressure drops. The main attention is paid to the filtration features of the process of desorbing gas flow in the seam. The developed model is based on the theory of inertia-free gas movement in two-scale interpenetrating porous media, differing by orders of magnitude in porosity and permeability. It is accepted that gas velocities in the seam are small, so the Darcy equation was used, written in each zone separately. The desorption component of the flow rate is determined by a linear relationship.

The calculations were carried out numerically using an explicit scheme. It is shown that the accuracy of the calculations is quite satisfactory. The change in pressure in two different channel systems is presented depending on the intensity of desorption and on the intensity of gas flow from one pore branch of the system to another. With intense flows, pressure differences between areas are insignificant. With weak flows, the differences are large, which should lead to large internal stresses. The effect of the desorption rate on the pressure distribution in the considered range of parameter changes is insignificant. Despite the fact that the pore channels in the considered medium belong to the same class, the patterns of filtration flows in channels of different sizes are very different from each other, which greatly affects the adsorption processes.

The detailing of the pore space presented in this article leads to a greater physical understanding of the kinetic stage of the mass transfer process in porous media.

Keywords: porous medium, gas, diffusion, mass transfer, filtration, desorption, microporous channels.

1. Introduction

Consideration of filtration and mass transfer processes in bidisperse porous layers has recently gained wide popularity. This is due to the fact that many porous bodies, for example, rocks and coal seams, are fractured-porous media, having, as it were, two characteristic sizes of porous channels. So in [1, 2] as a result of studies of the pore space of coal, the following conclusions were made that coal has extremely low porosity and permeability, but a high percentage of microcracks.

Measurements made in [2] showed two distinct increases in the distribution of pore channels by characteristic size: one in the region of twenty - thirty micrometers; the second, wider and higher, in the region of tenths and hundredths of micrometers. To some extent, these results are confirmed by studies of coal impregnation [3]. Such heterogeneity of the pore structure should lead to nonequilibrium of mass transfer processes, as was pointed out in [4].

The introduction of relaxation components into the porous structure, in particular, pore sizes that differ significantly from each other, has largely brought the theoretical results into agreement with experiment [5]. The ideas of bidispersity were used when considering unsaturated fluid flows in soils [6, 7], as well as when considering heat and mass transfer processes [8, 9]. In the last two works, bidispersity was transformed into a source of relaxation to study the initial period of the process.

An approach similar in mathematical description was used in [10], where a diffusion-filtration model of methane release from a coal seam was considered. In the latest work, it was possible to obtain the distribution of methane in a coal seam taking into account gas pumping due to desorption from blocks penetrated by a network of micropore channels. The issues covered in [10] are extremely relevant and not only in this specific area, so other formulations are also of interest.

The purpose of this work is to construct a high-quality physical picture of pressure changes in a complex pore space, characteristic of coal seams, which is of not only theoretical, but also practical interest, because this is due to safety issues.

Taking into account the above, to achieve this goal, it is necessary to construct a mathematical model of filtration flow in a two-scale pore system, taking into account gas desorption, which describes the most important initial stage of the process - pressure release from the seam. Let us base it on the theory of inertia-free gas movement in two-scale interpenetrating porous media that differ from each other in porosity and permeability [11].

2. Theoretical part

Let us consider the one-dimensional problem of gas desorption and filtration in a seam. But in contrast to the above-mentioned works, we consider filtration flow in pores, the sizes of which are very different from each other, but allow the gas medium to flow in these channels. The second group of small-scale channels shown in [2] can be divided into two zones: the first has channels of the order of 10^{-7} m or more, and the second - 10^{-8} m or less. Then, in the first group and in the first zone of the second group, one can still consider the filtration flow with adsorption and desorption of the substance on the surface of the channels, and in the second zone of the second group, according to the theory of volumetric filling, it is preferable to consider the diffusion transfer of the adsorbing or desorbing substance. Although the indicated size range practically does not extend beyond the boundaries of macropores according to the modern classification of porous systems [12], such a difference may affect the kinetic characteristics of mass transfer.

We assume that the pore space of the seam consists of two types of channels with diameters that are very different from each other, for example, 20 μm and 0.1 μm, but somehow connected with each other. Accepted assume that the gas velocities in the seam are small, therefore, the theory is based on the Darcy equation [13], written in each zone separately

$$u_J = -\frac{K_J}{\mu}\frac{\partial p_J}{\partial x}, \tag{1}$$

where u is filtration velocity, m/s; p – pressure, Pa; K – gas permeability, m^2; μ – coefficient of dynamic viscosity, Pa·s; index J – refers to a particular area. Let us now write out the equation for the conservation of mass in these two regions

$$\frac{\partial(\varepsilon_J \rho_J)}{\partial t} + \frac{\partial(\varepsilon_J \rho_J u_J)}{\partial x} = g_{AJ} + g_{PJ}, \tag{2}$$

where t – time, s; x – coordinate, m; ε – porosity; ρ – gas density, kg/m^3; g_A – flow rate associated with gas desorption, kg/(s·m^3); g_P – flow rate associated with gas flows from one porous structure to another, kg/(s·m^3).

Let us further assume that the seam is at a constant temperature T (for example, 293 K) and at a relatively low pressure ($p_N = 50 \cdot 10^5$ Pa), then from the gas equation of state

$$\rho_J = \frac{p_J}{RT}. \tag{3}$$

The flow rate for internal flows from the second region to the first, taking into account the large length of the process in time, will be determined as [8, 9, 12]

$$g_{P2} = S_{21}\rho_2 (p_2 - p_1), \tag{4}$$

where S_{21} are coefficient characterizing flow rate per unit length, s/(kg m). We determine the desorption component of the flow rate by the linear relation

$$g_{AI} = -Sw_J \gamma_J \left(p_J - p^*\right) / \, p_A, \tag{5}$$

where γ_J is the coefficient characterizing the intensity of deadsorption, kg/(s m ^{2}); Sw_J – value characterizing the internal surface, m^{-1} ; p^* – equilibrium gas pressure, which we also take as the initial pressure, Pa; p_A - atmosphere pressure.

The possibility of such an approximation is determined by an analogue in mass transfer, when the flow rate of some component is defined as $S_W \gamma \left(c - c^*\right)$ [14] (γ – coefficient, kg/(s m^2); c* - concentrations, respectively, current and limit). In addition, for Langmuir adsorption the relation [14] is well satisfied

$$\frac{da}{dt} = \omega \left(a - a^*\right), \tag{6}$$

where α - adsorption, kg/m^3; α^* – its limit value; ω – coefficient 1/s. Considering that in a certain area (see [12]) adsorption is almost linear to pressure, i.e. $\alpha = r \cdot p$ (r is the coefficient), then expression (5) may be acceptable for consideration.

Let us also introduce into relation (4) the inclusion coefficient of this equality β. It is due to the fact that when the surface of the channels is covered with adsorbed gas, then part of the connecting isthmus between them is covered (the throughput is less), so we assume that the coefficient β is linearly related to the total current porosity

$$\beta = 1 - \lambda \frac{\varepsilon_1^* - \varepsilon_1 + \varepsilon_2^* - \varepsilon_2}{\varepsilon_1^* + \varepsilon_2^*}, \tag{7}$$

where ε^* is a certain maximum porosity of a particular zone; λ is a certain coefficient that regulates the flow capacity (in our case it is taken equal to 0.9). At small values of λ (overgrown channels), the coefficient β is minimal; for clean channels, $\beta = 1$. In calculations, when the coefficient β reaches this value, it means that at a given point the adsorption film has disappeared. Now, from relation (5) we determine the law of change in the radius of the channel with the adsorption layer Rw_J

$$2\pi Rw_J \rho_A \frac{\partial Rw_J}{\partial t} = -g_{AJ}, \tag{8}$$

where ρ_A is the conditional mass density of the adsorption layer, which we take equal to 3000 kg/m^3 . Integration of this equation is carried out from some initial value Rw_{J0} to the final value Rw_J^*, which can be associated with local porosity in each zone

$$\varepsilon_J = \left(\frac{Rw_J}{Rw_J^*}\right)^2 \varepsilon_J^*. \tag{9}$$

Let us now make one more correction for gas permeability and internal surface. Taking into account the thickness of the adsorption layers, we assume that

$$K_J = \left(\frac{Rw_J}{Rw_J^*}\right) K_J^* \qquad \text{and} \qquad Sw_J = \left(\frac{Rw_J}{Rw_J^*}\right) Sw_J^*, \tag{10}$$

where K_J^*, Sw_J^* – limiting values of gas permeability and internal surfaces without adsorption layers. If, for assessment, Sw_J^* we imagine a porous system in the form of straight tubes (this is the simplest, but still widely used system of pore channels [11]), then per unit area $Sw_J^* = N_J \cdot 2\pi Rw_J^{*2}$, where $N_J = \dfrac{\varepsilon_J}{\pi Rw_J^{*2}}$ is the number of such tubes per square meter. Let us now write down the main equations in the form

$$\frac{\partial(\sigma_1)}{\partial\tau} + \frac{\varepsilon_1^*}{\varepsilon_1}\frac{K_1}{K_1^*}\frac{\partial^2(\sigma_1^2)}{\partial\zeta^2} = \frac{RT}{\varepsilon_1 p_A} T_M \cdot \gamma \cdot Sw_1(\sigma_0^* - \sigma_1) + \beta\frac{p_A\sigma_2}{\varepsilon_1} T_M S(\sigma_2 - \sigma_1), \tag{11}$$

$$\frac{\partial(\sigma_2)}{\partial\tau} + \frac{\varepsilon_1^*}{\varepsilon_2}\frac{K_2}{K_1^*}\frac{\partial^2(\sigma_2^2)}{\partial\zeta^2} = \frac{RT}{\varepsilon_2 p_A} T_M \cdot \gamma \cdot Sw_2(\sigma_0^* - \sigma_2) - \beta\frac{p_A\sigma_2}{\varepsilon_2} T_M S(\sigma_2 - \sigma_1), \tag{12}$$

where $\sigma_J = p_J / p_A$; $\tau = t/T_M$; $\zeta = x/h$; $T_M = 2\dfrac{\varepsilon_1^* h^2}{K_1^* p_A}\mu$ – time scale, (h – seam width, m). In these calculations, the width of the seam is taken to be 1 m, and the time scale T_M is equal to 78.4 s. The boundary conditions for equations (11) and (12) are the relations:

at $\zeta = 0$

$$\frac{\partial \sigma_1}{\partial \zeta} = \frac{\partial \sigma_2}{\partial \zeta} = 0, \tag{13}$$

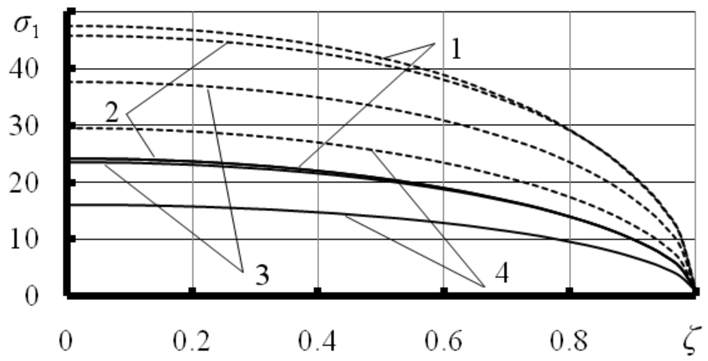
at $\zeta = 1$

$$\sigma_1 = \sigma_2 = 1. \tag{14}$$

3. Results and discussion

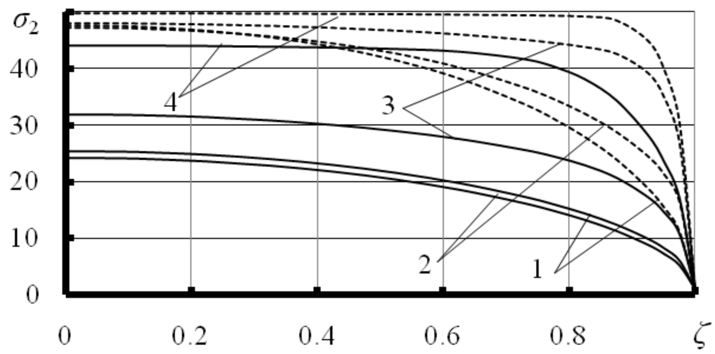
In the calculations, based on the results of work [2], we assume that $\varepsilon_1^* = 0.02$, $\varepsilon_2^* = 0.1$, and the conditional radii of the capillaries $Rw_1^* = 20 \cdot 10^{-6}$ m, $Rw_2^* = 10^{-7}$ m. In accordance with [15], we take the gas permeability coefficients K_1^* and K_2^* equal to 10^{-13} m^2 and 10^{-15} m^2.

Figures 1 and 2 show curves of changes in relative pressure across the width of the seam (1 m) for two points in time at different values of S_{21}.



curves 1 – $S_{21} = 10^{-6}$, 2 – 10^{-7}, 3 – 10^{-8}, 4 – 10^{-9}; dotted curves $\tau = 0.008$, solid curves $\tau = 0.062$

Figure 1 – Pressure changes in area 1 across the width of the seam ($\gamma = 10^{-3}$)

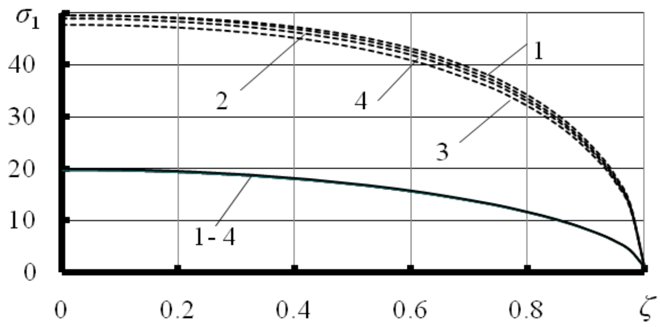


curves 1 – $S_{21} = 10^{-6}$, 2 – 10^{-7}, 3 – 10^{-8}, 4 – 10^{-9}; dotted curves $\tau = 0.008$, solid curves $\tau = 0.062$

Figure 2 – Pressure changes in area 2 across the width of the seam ($\gamma = 10^{-3}$).

From Figure 1 and Figure 2 it is clear that the pressure in each of the areas drops over time, reaching atmospheric pressure at the outer boundary of the seam. As the coefficient S_{21} decreases, the curves in region 1 go lower than the curves in region 2, while at the initial moment significant pressure gradients arise (dotted curves 3, 4 in Figure 2). This is natural, since flows between regions are decreasing. It is also clear from Figure 1 that the first three curves in region 1 for $\tau = 0.06$ are very close to each other. This indicates that at large times the curves should merge with each other.

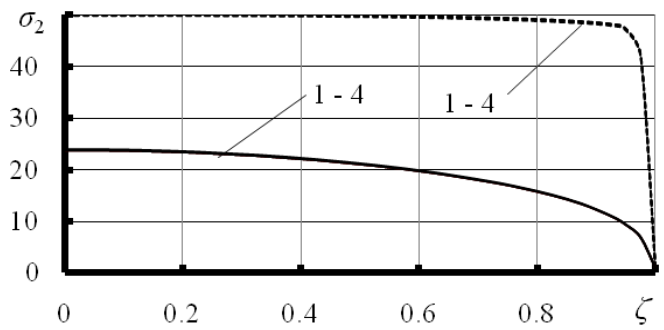
Let us now show the curves for the case when S_{21} is constant, for example, $5\cdot10^{-8}$, and γ varies within wide limits, in particular: 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}. From Figure 3 and Figure 4 it follows that the value of γ has little effect on the pressure distribution. From Figure 3 it is clear that only for a short time the curves are somewhat fluffy; for a longer time, within the scale of the figure, they practically merge.



curves 1 – $\gamma = 10^{-3}$, 2 – 10^{-4}, 3 – 10^{-5}, 4 – 10^{-6}; dotted curves $\tau = 0.01$, solid curves $\tau = 0.1$

Figure 3 – Pressure changes in area 1 across the width of the seam ($S_{21} = 5\cdot10^{-8}$).

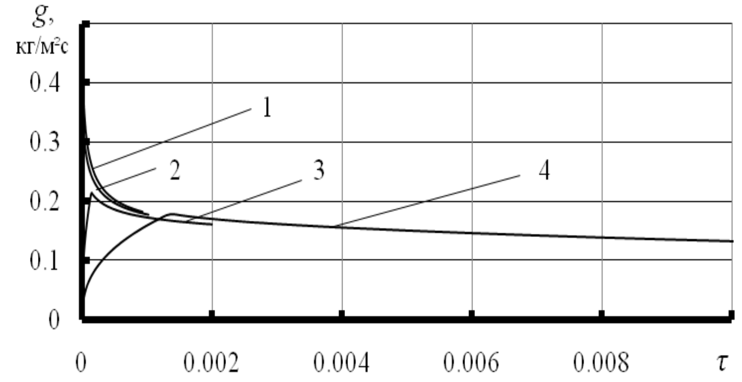
In Figure 4, both for short and large time, the curves on the scale of this figure are also merged. The consistency of the curves for a long time indicates that the gas mass ($G = \rho\int_0^t (u_1 + u_2)dt$) leaving the channels at $\zeta = 1$ should be the same. Let us present these values for $\tau = 0.09$: at $\gamma = 10^{-3}$ $G = 0.6142$ kg/ m^2 ; at $\gamma = 10^{-4}$ $G = 0.6126$ kg/m^2; at $\gamma = 10^{-5}$ $G = 0.6085$ kg/ m^2; at $\gamma = 10^{-6}$ $G = 0.6154$ kg/m^2 . Considering that the coefficient γ determines the rate of desorption, and not the amount of gas released, the numbers given indicate the accuracy of the calculation, since the error is less than one percent of the average value, the accuracy is quite satisfactory.



curves 1 – $\gamma = 10^{-3}$, 2 – 10^{-4} , 3 – 10^{-5} , 4 – 10^{-6}; dotted curves – $\tau = 0.001$, solid curves – $\tau = 0.09$

Figure 4 – Changes in pressure in area 2 across the width of the seam ($S_{21} = 5\cdot10^{-8}$).

In conclusion, we will show curves of changes in the flow rate of gas leaving the pore space of the formation over time for the case when narrow pores are clogged and gas comes out only from wide pores



Curves 1 – $\gamma = 10^{-3}$, 2 – 10^{-4} , 3 – 10^{-5} , 4 – 10^{-6}

Figure 5 – Change in flow rate over time ($S_{21} = 2\cdot 10^{-8}$).

In this case, boundary condition (14) has a slightly different form:

at $$\zeta = 1 \quad \sigma_1 = 1, \quad \frac{\partial \sigma_2}{\partial \zeta} = 0. \qquad (15)$$

Figure 5 shows the curves $g = \rho(u_1 + u_2)$ at $\zeta = 1$ from the beginning of the filtration process to the time of disappearance of the adsorbed film up to the point $\zeta = 0$. This figure clearly shows the influence of the parameter γ. At relatively large γ (curves 1, 2), the desorption process occurs quickly; for the fourth option, it is delayed and ends at the point $\tau = 0.01022$. The graph shows that the flow rate first increases and then begins to decrease. The increase is associated with the opening of the pore, and the subsequent decrease is associated with a decrease in pressure.

4. Conclusions

The problem of desorption and filtration of gas in seam with double permeability is considered. A mathematical model has been created that takes into account the two-scale nature of the pore system. The influence of internal flows on the pressure distribution in each region is shown. With intense flows, the pressure drops between regions are insignificant; with weak flows, the differences are large, which should lead to large internal stresses. The effect of the desorption rate on the pressure distribution in the range of changes in our parameters is insignificant. Despite the fact that the considered pore system belongs to the same class of pore channels, the patterns of filtration flows can differ greatly from each other, which can greatly influence adsorption processes.

Thus, taking into account the heterogeneity of the pore space when constructing a mathematical model leads to a more complete description of the physical process under consideration.

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ФІЛЬТРАЦІЯ ДЕСОРБУЮЧОГО ГАЗУ У БІДИСПЕРСНОМУ ПОРИСТОМУ ШАРІ

Єлісєєв В., Луценко В.

Анотація. Актуальність розгляду фільтраційних завдань з урахуванням адсорбційно-десорбційних процесів пов'язана з безпекою гірничих та вугільних розробок за наявності в породі адсорбованих газових відкладень, а також при вирішенні екологічних завдань, зокрема зберігання парникових газів у ґрунтах та вугільних пластах.

У цій роботі, згідно з сучасними уявленнями, пористе середовище представлено у вигляді двох типів порових каналів, гідродинамічно пов'язаних один з одним, але які сильно відрізняються один від одного своїми характерними діаметрами. Також прийнято, що поверхні каналів обох типів покриті твердим осадом адсорбованого газу, який починає виділятись при скиданні тиску. Основна увага приділяється фільтраційним особливостям процесу течії газу, що десорбується, в пласті. В основу розробленої моделі покладено теорію безінерційного руху газу у взаємопроникних пористих середовищах, що на порядки відрізняються один від одного проникністю. Вважаємо, що швидкості газу в пластах невеликі, тому використано рівняння Дарсі, записане в кожній зоні окремо. Десорбційну складову витрати визначено лінійним співвідношенням.

Розрахунки проведені чисельно з допомогою явної схеми. Показано, що точність розрахунків є цілком задовільною. Наведено зміну тиску у двох різних канальних системах залежно від швидкості десорбції та від інтенси-

вності перетікання газу з однієї порової гілки системи до іншої. При інтенсивних перетіканнях перепади тиску між областями незначні. При слабких перетіканнях, перепади великі, що повинно призводити до великих внутрішніх напруг. Вплив швидкості десорбції на розподіл тиску в розглянутому інтервалі зміни параметрів незначний. Незважаючи на те, що порові канали в розглянутому середовищі відносяться до одного класу, картини фільтраційних течій у каналах різних розмірів сильно відрізняються один від одного, що значною мірою впливає на адсорбційні процеси.

Наведена у цій статті деталізація порового простору призводить до більшого фізичного розуміння кінетичної стадії процесу масообміну в пористих середовищах.

Ключові слова: пористе середовище, газ, дифузія, масообмін, фільтрація, десорбція, мікропорові канали.