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Study of the migration processes in the roof of an underground gas-generator

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Abstract. Currently, coal is the main natural energy carrier in Ukraine due to its limited resources of oil and natural gas. A promising method for extracting coal is underground gasification using thermochemical and mass-exchange processes. This study was aimed at the investigation of migration processes in the roof rock of an underground gas-generator through developing a physical-

mathematical model of migration of gasification products in the roof rocks of an underground gas-generator. We have substantiated the technological measures directed to eliminating the hydrocarbon zones, with additional extraction of useful products. We suggest a physical-mathematical model of migration of gasification processes in the roof rocks of an underground gas-generator, which allows elimination of hydrocarbon zones with additional extraction of useful products. We determined the pattern of the changes in the excess pressure and temperature during the processes of gasification in overburden, moisture content of the gas during its seepage through the roof rocks, and also colmatage of the porous space. Using the results, we improved the UCG technology by using the condensing products of gasification in the overburden.

Key words: ground water, underground coal gasification, migration of coolants, underground gas-generator, thermal energy

Исследование процессов миграции в породной кровле подземного газогенератора

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Аннотация. На сегодняшний день уголь в Украине является основным природным энергоносителем ввиду ограниченности запасов нефти и природного газа. Перспективным способом добычи и переработки угля является подземная газификация посредством термохимических и массообменных процессов. Цель данной работы - исследование процессов миграции в породной кровле подземного газогенератора путем создания физико-математической модели миграции продуктов газификации в породах кровли подземного газогенератора. Обоснованы технологические меры, направленные на ликвидацию углеводородных зон с дополнительной добычей полезных продуктов. Установлены закономерности изменения избыточного давления и температуры в процессе газификации в покрывающих породах, влагосодержания газа при фильтрации его по породам кровли, а также коагуляции порового пространства. На основании полученных результатов усовершенствована технология ПГУ путем использования конденсирующихся продуктов газификации в покрывающих породах.

Ключевые слова: подземные воды, подземная газификация угля, подземный газогенератор, миграция теплоносителей, тепловая энергия

Introduction. The insufficiency of reserves of oil and natural gas in Ukraine has led to coal becoming the country's main natural energy carrier. Increasing its underground extracting is related to increasing the depth of mining works; increase in the amount of the rock tailings; worsening of the air basin conditions and, therefore disorders in the stability of the natural environment. A promising method of

rationalizing the extraction and proccession of coal is its underground gasification using thermochemical and mass-exchange processes.

Domestic and foreign scientific-practical experience in gasification of coal seams (Kreynin, 2008; Timoshuk, 2012) indicates the priority of decreasing the uncontrolled leakages of the gas gener-

ated, which causes unproductive energy use and saturation of the overburden with products of gasification. Increase in the cost-effectiveness of the underground coal gasification (UCG) and neutralization of its negative impact on the rock structure requires working out the correct the gas-hydrodynamical regime of this process. The efficiency of gasification could be significantly increased using using the liquid products of gasification which accumulate in the rock roof due to their expulsion into the reaction channel and further extraction to the surface, hence the necessity of studying the migration processes around an underground gas-generator, which is the objective of this study.

Substantiation of the model of migration.

The main physical-chemical processes which occur in the overburden rocks during UCG are transfer of gas and liquid products of gasification, and also their interaction. The complexity of the filtration processes in the roof rocks is related to a number of factors, including: 1) complex composition of the gas produced; 2) occurrence of phase transitions; 3) change of collecting and physical properties of the overburden over time as a result of colmatage of pores with products of incomplete burning, and also of condensation of filtrating gas; 4) simultaneous joint flow of the condensational mixture, gas and water, which are isolated phases. It should be considered, that two- or three-phase flow practically always occurs during a formation of condensational mixture, for the forces which move the condensate are the result of hydrodynamic pressure of gas or water, and also conditioned by their elastic properties.

In such conditions, in overburden, a multi-phase seepage of complex multi-component mixture takes place in overburden, in which an intense heat exchange occurs between the phases which move at different speeds. The transition of separate components from the one phase into the other leads to change in the compounds and physical properties of the filtrated phases. Therefore, a mathematical model of multi-phase filtration is quite cumbersome and includes a variety of parameters, which are not always possible to accurately determine.

An efficient and quite simple method of describing a multi-phase flow is a macroscopic method (Dmitriyev, 2003), based on physical laws of mass conservation for every separate phase with consideration of their interphase interaction in the form of additional members in the equations. Therefore, with the joint flow of two (or more) fluids, it is considered that each of them occupies only part of porous space. The saturation S_i of a porous environment is determined as a share of the volume of the active pores occupied by this phase

$$S = V_{\phi} / V_n,$$

where V_{ϕ} , V_n – are volume of the phase and active pores in the filtrating environment respectively.

Due to selective moistening of solid rocks with water, the contact area of every phase with the frame of the porous environment is significantly higher than the contact area of the phases with one another – this allows one to consider that the main contribution to the resistance against the flow causes interaction between every fluid and the solid frame of the overburden, and also allows one to disregard the effect of viscous contact of one fluid with the other. Naturally, the resistance occurring in every phase at joint filtration, is different from that which would occur in the flow of only one of them.

It has been experimentally determined (Maksimov, 1976) that the discharge of every phase increases following the increase in pressure difference and saturation of the given phase. The law of filtration of every phase (generalized Darcy's law) can be written as follows

$$\omega_i = -\frac{\kappa}{\mu_i} \kappa(s) \cdot (\nabla P_i - \rho_i^0 g),$$

where ω_i – speed of filtration of the i -st phase; κ – absolute penetrability of the seam; μ_i – coefficient of dynamic viscous phase; ∇P_i – difference in the pressure in the phase; ρ_i^0 – actual density of the i -st phase; g – acceleration of free fall; $\kappa(s)$ – relative penetrability of the phase, which depends on the absolute penetrability of the environment and saturation of every phase.

The connection between the pressure in the phases is determined by the following equality

$$P_2 - P_1 = P_{\kappa}(S) = \alpha_n \cos \theta \sqrt{n/\kappa} J(S),$$

where α_n – coefficient of interphase tension; θ – statistical wetting contact angle between the fluids and the rock; n – porosity of the environment; $J(S)$ – non-dimensional Leverett function.

This condition means that the difference of pressure in two phases $P_2 - P_1$ equals capillary pressure P_{κ} , which is a familiar experimental saturation function.

The impact of gravitational and capillary forces in the process of multi-phase filtration can be calculated using non-dimensional parameters N_g and N_c , which characterize the ratio of the gravity and capillary forces to viscous forces respectively

$$N_g = \frac{\kappa \cdot \Delta \rho g \sin \alpha}{\mu \omega},$$

$$N_c = \frac{\alpha_n \cdot \cos \theta \sqrt{n \kappa}}{\mu \omega L}, \quad (1)$$

where $\Delta \rho = \rho_2^0 - \rho_1^0$, L – the value of filtration area.

The gravitational effect can be disregarded, if the parameter N_g is low compared to the value, which occurs if the difference in the static gradients of the pressure of phases is much lower than the hydrodynamic gradient of pressure. In the conditions typical for UCB, the area of flow of phases which are filtrated in the overburden, does not exceed dozens of meters, pressure differences on the borders (rock contour of the underground gas-generator and the surface) is quite high, whereas the difference in the static gradients of phase pressure has the following order 10^3 Pa/m . Therefore, during the filtration of multi-component mixture in the overburden $N_g \ll 1$, the gravitational forces can be disregarded.

For calculating the impact of capillary forces, we should note, that the interphase tension on the border of most hydrocarbon fluids and gases with water is within 0.03 to 0.005 H/m ; speed of filtration on average equals $10^{-5} - 10^{-4} \text{ m/s}$. After adding (1) $\alpha_n = 0,03 \text{ H/m}$, $\cos \theta \approx 1$, $n = 0,3$, $\kappa = 10^{-13} \text{ m}^2$, $\mu = 3 \cdot 10^{-3} \text{ Pa} \cdot \text{s}$, $\omega = 10^{-4} \text{ m/s}$, $L = 100 \text{ m}$, we receive the value 10^{-4} for the capillary parameter N_c , which, considering the carefulness of the estimation, indicates the low value of this magnitude.

In cases when the filtrating phases are elastic, the impact of compressibility on the distribution of the saturation can be disregarded. Thus, the typical time of non-stationary redistribution of the pressure due to compressibility of the phases is calculated using the ratio

$$t_1 = L^2 / a,$$

and the time of multi-phase filtration is calculated using the expression

$$t_2 = L / \omega,$$

the ratio of periods is equal

$$t_1 / t_2 = \omega L / a \approx 10^{-2},$$

where a – coefficient of piezo conductivity, $1 \text{ m}^2/\text{s}$.

Therefore, non-stationary processes of elastic redistribution of the pressure fade at the beginning of the filtration process in the overburden rocks, and the moving phases can be considered incompressible.

With one-dimensional flow of incompressible fluids in the conditions when the surface tension between the phases is low and the capillary pressure and also the impact of gravitational forces can be disregarded, the mathematical description of the process of multi-phase filtration could be simplified, as first suggested by the American researchers S Buckley and M Leverett (1963). This model is reflected by a homogenous equation for the saturation of the pressurizing phase and is expressed as follows

$$\frac{\partial S}{\partial \tau} + f'(S) \frac{\partial S}{\partial \zeta} = 0,$$

Where the non-dimensional independent variables τ and ζ are determined using the equalities

$$\tau = \int_0^t \frac{w(t')}{nL} dt'; \zeta = \frac{z}{L},$$

And the Buckley-Leverett function is expressed using relative phase penetrability

$$f(s) = \frac{\kappa_1(s)}{\kappa_1(s) + \mu_0 \kappa_2(s)},$$

where $w(t)$ – total speed of filtration of phases; z – dimensional coordinate; μ_0 – ratio of the coefficient of viscosity of the phases ($\mu_0 = \mu_1 / \mu_2$).

The non-linear pattern of the accepted equations and the methods of their solution in many ways depend on the type of functional ratios which define the properties of fluids and porous collector in relation to the variables calculated: pressure, saturation, concentration, temperature. Usually, the most nonlinearities in the equations of filtration are related to the type of dependencies between relative phase penetrabilities, capillary pressure and the saturations (Fig. 1).

Fig. 1. Typical dependencies between relative phase penetrabilities, capillary pressure and water saturation in the system “condensate-water”

Saturation s_{wc} which causes water to move is called connate saturation, and the saturation which stops the pressurizing phase (condensate) is called residual saturation s_{or} . Therefore, $1 - s_{or}$ is maximum water saturation in which two-phase flow occurs. At $s_w < s_{wc}$ the phase penetrability of water equals zero. A similar pattern characterizes the dependency between relative phase penetrability and saturation for the two-phase system “gas-water”.

In the suggested model of multi-phase filtration, the gas flow is described using the system of equations which consider the pressure change, convective heat-conductivity and the ratio of condition parameters

$$a^2 \frac{\partial^2 P}{\partial z^2} = \frac{\partial P}{\partial t}; \quad (2)$$

$$v_z = - \frac{\kappa}{\mu_z} \cdot \frac{\partial P}{\partial z}; \quad (3)$$

$$\lambda_n \cdot \frac{\partial^2 T}{\partial z^2} + c_z \cdot v_z \cdot \frac{\partial T}{\partial z} = c_n \cdot \frac{\partial T}{\partial t}; \quad (4)$$

$$\rho_z = \frac{\rho_n \cdot P \cdot T_n}{P_n \cdot T \cdot \eta}, \quad (5)$$

where P, T – pressure and temperature of gas; a – coefficient of piezo conductivity of the filtrating environment; κ, λ_n, c_n – coefficients of penetrability, heat-conductivity and volumetric heat capacity of the overburden rocks; ρ_z, μ_z, c_z – density, viscosity and volumetric heat capacity of the filtrated gas; ρ_n – density of gas mixture in normal conditions ($T_n = 273,15K$ and $P_n = 1,01325 \cdot 10^5 Pa$); η – coefficient of gas compressibility.

Porosity and penetrability of overburden rocks change as a result of colmatage of the pores of the filtrating environment with products of incomplete combustion, and also due to the physical-chemical interaction of the UG and the rock. The scheme of changes in porosity of a penetrable collector during gas filtration, developed using the results of physical modeling of UCG, indicates absence of colmatage agents in the pores of rocks at distances greater than 2.5 m from the gas-generator.

The change in gas viscosity μ_z in relation to the temperature T is expressed using Sutherland's formula (Golubev, 1959)

$$\mu_T = \mu_n \cdot \frac{1 + \frac{C}{T_n}}{1 + \frac{C}{T}} \cdot \sqrt{\frac{T}{T_n}}, \quad (6)$$

where μ_n, T_n – viscosity and temperature of gas in normal conditions; C – Sutherland's constant.

The volumetric heat-capacity of gas and the rock is calculated using the expression

$$c_z = \rho_z \cdot c'_z; c_n = \rho_n \cdot c'_n, \quad (7)$$

where ρ_z, c'_z – density and specific heat of gas; ρ_n, c'_n – density and specific heat of the filtrating environment

Density of the rock which is being saturated with UC components can be calculated as follows. The parts of the elementary volume of a porous environment (volume share) $\psi_m, \psi_{ж}$ и ψ_r , occupied by the solid body, fluid and gas respectively are calculated using the equation

$$\begin{aligned}\psi_m &= 1 - n_0; \\ \psi_{\text{жс}} &= n_0 - n; \psi_{\Gamma} = n,\end{aligned}\quad (8)$$

where n_0 – porosity of the filtrating environment before the gasification

The density of the rock equals the total of the partial densities of its components

$$\rho_n = \psi_m \cdot \rho_{\text{ск}} + \psi_z \cdot \rho_z + \psi_{\text{жс}} \cdot \rho_{\text{жс}}, \quad (9)$$

where $\rho_{\text{ск}}, \rho_{\text{жс}}$ – density of the frame and condensation of moisture.

For calculating the coefficient of heat-conductivity of overburden rocks saturated with gasification products, the Schuman Voss method is used

$$\begin{aligned}\lambda_n &= \lambda_{\text{н.ф.}} \cdot \Phi^3 + (1 - \Phi^3) \cdot \lambda''' + \Delta; \\ \Phi &= \Pi \cdot (\Pi + 1) \cdot \ln \frac{1 + \Pi}{\Pi} - \Pi; \\ \lambda''' &= \frac{\lambda_{\text{ск.}} \cdot \lambda_{\text{н.ф.}}}{\lambda_{\text{н.ф.}} + \Pi \cdot (\lambda_{\text{н.ф.}} - \lambda_{\text{ск.}})} \cdot \\ &\cdot \left\{ 1 + \frac{\Pi \cdot (1 + \Pi) \cdot (\lambda_{\text{н.ф.}} - \lambda_{\text{ск.}})}{\lambda_{\text{н.ф.}} + \Pi \cdot (\lambda_{\text{н.ф.}} - \lambda_{\text{ск.}})} \cdot \ln \frac{\lambda_{\text{н.ф.}} \cdot (1 + \Pi)}{\lambda_{\text{ск.}} \cdot \Pi} \right\}; \\ \Delta &= 2,241 + 0,0129 \cdot \frac{\lambda_{\text{ск}}}{\Phi},\end{aligned}\quad (10)$$

where $\lambda_{\text{н.ф.}}$ - heat conductivity of the phase which saturates the filtrating environment; $\lambda_{\text{ск.}}$ - heat conductivity of the rock frame; Π - ratio of the frame volume to the total volume of the environment.

The heat conductivity of the saturating phase can be calculated using the formulae

$$\begin{aligned}\lambda_{\text{н.ф.}} &= 0,5 \cdot (\lambda' + \lambda''); \\ \lambda' &= (1 - \frac{n}{n_0}) \cdot \lambda_{\text{жс}} + \frac{n}{n_0} \lambda_z; \\ \lambda'' &= \frac{1}{\frac{(1 - n/n_0)}{\lambda_{\text{жс}}} + \frac{n}{n_0 \cdot \lambda_z}},\end{aligned}\quad (11)$$

where $\lambda_{\text{жс}}$ – heat conductivity of the condensate moisture; λ_z - heat conductivity of gas.

To solve the equations (2-5), the initial conditions were considered to be

$$\begin{aligned}T(z, t)|_{t=0} &= T_0(z), \\ P(z, t)|_{t=0} &= P_0(z),\end{aligned}\quad (12)$$

where $T_0(z)$, $P_0(z)$ – the initial temperature and pressure of the overburden rocks respectively.

The solving of the equation of heat transfer (4) considers that at the inflow border ($z=0$), the heat flow transferred via gas equals the conductive flow

$$\left(-\lambda_n \frac{\partial T}{\partial z} + v_z \cdot c_z \cdot T \right) \Big|_{z=0} = v_z \cdot c_z \cdot T_n, \quad (13)$$

where T_n, v_z – the initial temperature and the speed of filtration of the overheated gas mixture respectively.

At a distance from the gas-generator, a condition of temperature constancy takes place

$$\frac{\partial T}{\partial z} = 0. \quad (14)$$

Under the given border and initial conditions (12)-(14), the distribution of temperature in a partly limited area can be calculated using the following equation (Aver'yanov, 1965, Fomichov, 2014)

$$T(z, t) = T_0 + (T_n - T_0) \cdot F(z, t),$$

$$\begin{aligned}F(z, t) &= \frac{1}{2} \{ \operatorname{erfc} \varphi_2 - (1 + \xi + \tau) \cdot \\ &\cdot e^{\xi} \cdot \operatorname{erfc} \varphi_1 + 2 \cdot \sqrt{\frac{\tau}{\pi}} \cdot e^{-\varphi_2^2} \},\end{aligned}\quad (15)$$

$$\begin{aligned}\varphi_{1,2} &= \frac{\xi \pm \tau}{2 \cdot \sqrt{\tau}}, \quad \xi = \frac{v' \cdot z}{b}, \quad \tau = \frac{v'^2 \cdot t}{b}, \\ v' &= v_z \cdot \frac{c_z}{c_n}, \quad b = \frac{\lambda_n}{c_n}.\end{aligned}$$

Testing of the model. The solving of the equations (2)-(5) with consideration of the equations (6)-(14) in the form (15) was conducted in the MatCad programme environment. At given border conditions, the number of calculation points was calculated regarding the conditions of z and interval of counting. In the beginning of the calculating cycle, the given temperature was the temperature forming on the rock contour of an underground gas generator in the process of gasification. Then, an iterative calculation of temperature with accuracy of 1°C was made. If the difference between two consequent values of temperature was higher than the considered accuracy, the coefficients and expressions (15) were recalculated with lower difference in the tempera-

tures. The process of iterated function was conducted until the given accuracy was achieved. The filtration speed was calculated using the averaged value of the pressure calculated at every interval of counting. During the transition to the next interval, the initial temperature was considered equal to the temperature on the previous interval.

Figs. 2 and 3 provide the results of calculating of the pressure and temperature in the overburden rocks in the process of UCG for the conditions of the Synelnykovo brown coal deposits ($n_0 = 0,35$; $\kappa_0 = 10^{-12} \text{ m}^2$; $c_n' = 795,49 \text{ J/kg} \cdot \text{deg}$; $\rho_{\text{naq.}} = 1,18 \text{ kg/m}^3$; $\mu_n = 1,43 \cdot 10^{-5} \text{ Pa} \cdot \text{s}$; $\rho_n = 1500 \text{ kg/m}^3$; $P_{\text{naq.}} = 3 \cdot 10^5 \text{ Pa}$; $T_{\text{naq.}} = 900 \text{ C}^0$). For comparison, Fig. 2 provides the curve of temperature change, obtained using the results of physical modeling (Sado-venko, 2006).

The zone of potential forming of condensate moisture in overburden rocks was determined using the nomogram of the water capacity of the natural gases (Basniyev, 1978). Using the known values of pressure and temperature, we developed the curve of change in gas moisture content along the filtration route (Fig.4).

The analysis of the obtained results indicates a decrease in the water content in the gas from 300 to 10 g/m³ (limit of gas saturation at $T_0 = 15 \text{ C}^0$) at the distance of 0.5-2.5 m from the gas generator. Therefore, 96% of liquid hydrocarbons from UCG gas leakage condensed in this zone. According to the balance for averaged regime of gasification process, we can calculate the average discharge of condensate moisture, which reaches 0.08 m³/h.

Fig. 2. Change in the temperature (T) in overburden rocks at the distance (z) from the gas generator: 1 – calculated; 2 – obtained using physical modeling.

Fig. 3. Change in the gas pressure (P) in overburden rocks over time at the distance (z) from the gas generator: 1-3 days; 2-5 days; 3-8 days.

Fig. 4. Change in the water content of UCG gas (W) along the filtration route (z) in overburden rocks with penetrability: 1 – 10^{-11} m^2 ; 2 – 10^{-12} m^2 ; 3 – 10^{-13} m^2

Conclusions. The proposed physical-mathematical model of migration of gasification products in the roof rocks of an underground gas generator allows one to validate the technological measures, aimed at eliminating hydrocarbon zones with additional extraction of useful products. Using the results of mathematical modeling, we determined the following patterns:

- During the process of gasification, the excessive pressure and the temperature rapidly decrease at an insignificant distance in overburden rocks;
- During the gas filtration, the water content of the gas in the roof rocks; decreases from 300 g/m^3 near the gas generator to 10 g/m^3 at a distance of 2.5 m
- Sedimentary condensation moisture colmatages the porous space.

The obtained results facilitate the improvement of UCG technology by using the condensation products of gasification in the overburden rocks.

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