Two-phase model of thermal decomposition of shale stratum

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There are various methods of oil shale thermal processing with the purpose to generate primary energy product – so-called shale gas – however, methods that do not require the extraction of rock to the surface are of special interest [1]. In these methods, shale gas is extracted directly from the stratum as it is heating up, in one way or another.

The aim of this work is to build a model of thermal decomposition of shale strata when they are heated by electromagnetic field.

The model takes into account the phenomenon of thermal conductivity, interphase heat and mass transfer, thermal effect of chemical reactions and gas flow in the pores.

Due to significant anisotropy of properties, shale stratum can be represented in the form of a solid porous plane, which has evenly distributed heat sources formed by electrodes, the distance between which L is much larger than their radii R_0.

The geometry of the computational domain is shown in Fig. 1. Obviously, the challenge is to find the temperature distribution only in the destination area including one source with coordinates $(L/2, L/2)$.

Under the influence of an alternating electric field oil shale is heated by heat associated with its polarization, as well as by Joule heat caused by the conduction current.

When heated, solid phase reagent A_S that forms the shale skeleton, decomposes into a solid product B_S and gas B_G coming into the pores. At the initial time some quantity of the gas G_R, which is identical in composition to the B_G, is already contained in the pores. In turn, when heated, the gas G_R transforms into the gas G_p. Thus, the chemical reactions of the shale decomposition can be represented by the following conventional pattern:

$$A_S \xrightarrow{K_1} B_S + B_g$$

$$G_R \xrightarrow{K_2} G_p$$
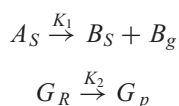
where K_1, K_2 – rates of reactions.

During decomposition the dominant mechanism of heating is subject to change: at first the effect is associated mainly with the dielectric losses, then due to accumulation of the product B_S Joule heating is prevalent.

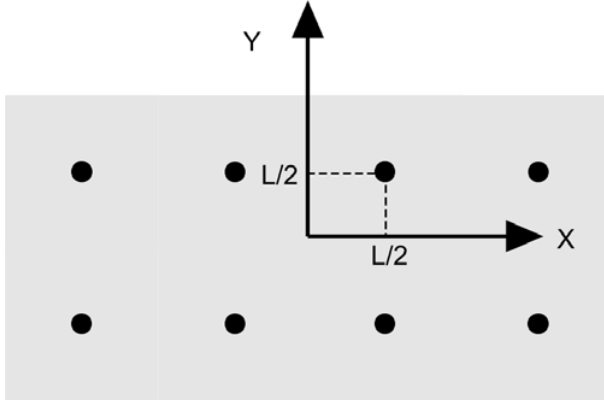[a] Corresponding author: masloaleksey@rambler.ru

Figure 1. Illustration for the problem formulation.

Calorimetric measurements of shale thermal decomposition [2] have shown that the summarized thermal effect of shale decomposition reaction is positive, and at the initial stage of kerogen decomposition endothermic effects are taking place. On further temperature raising the exothermic stage starts, coinciding with the secondary gasification. We assume that thermal effect of solid phase decomposition is negative, and that gaseous product reacts with heat release, and besides, exothermal heat effect is prevalent.

The equation of thermal conductivity for solid phase is as follows:

$$c_s \rho_s \frac{\partial T_s}{\partial t} = \lambda_s \nabla \cdot (\nabla_k T_s) + Q_1 W_1 + \Phi_s - \frac{\alpha_T}{1 - \varsigma} \left(T_s - T_g \right),$$

where T_S, c_S, ρ_S – temperature, heat capacity and density of the solid phase, accordingly; t – time, x, y – spatial coordinates; λ_s – coefficient of heat conductivity of the solid phase, W_1 – chemical source (drain) of heat, Φ_s – heat source associated with the effect of electromagnetic field on solid phase (depends on the location of the electrodes, their radii, characteristics of the electric field) [3], α_T – coefficient of heat transfer between gas and solid phase; ς – porosity; T_g – gas temperature.

Thermal effect of alternating electromagnetic field consists of a resistance and dielectric losses:

$$\Phi_S = \eta_{B_S} \sigma_1 E^2 + \left(1 - \eta_{B_S} \right) \varepsilon_1 \varepsilon_0 \Gamma E^2 tg\delta_1$$

where $E^2 = E_x^2 + E_y^2$ – squared electric field intensity; $E = E(x, y)$, σ_1 – conductivity, f – frequency, ε_1 –permittivity of hard rock, ε_0 – dielectric constant, $tg\delta_1$ – angle tangent (ratio) of dielectric losses.

Shares of the products of the solid phase reaction are defined by the following equations:

$$\frac{d\eta_{B_S}}{dt} = k_1 \left(1 - \eta_{B_G} - \eta_{B_S} \right) \exp \left(-\frac{E_1}{RT_s} \right) \nu_S,$$

$$\frac{d\eta_{B_G}}{dt} = k_1 \left(1 - \eta_{B_G} - \eta_{B_S} \right) \exp \left(-\frac{E_1}{RT_s} \right) \nu_g - \frac{\alpha_m}{1 - \varsigma} \left(\eta_{B_G} - \eta_G \right)$$

where k_1 – pre-exponential factor, E_1 – activation energy of the solid phase reaction, R – gas constant, ν_S, ν_g – stoichiometric coefficients for the solid phase reaction.

Equation of heat transfer in the gas phase is as follows:

$$c_g \rho_g \frac{dT_g}{dt} = Q_2 W_2 + \Phi_g + \frac{\alpha_T}{\varsigma} \left(T_s - T_g \right),$$
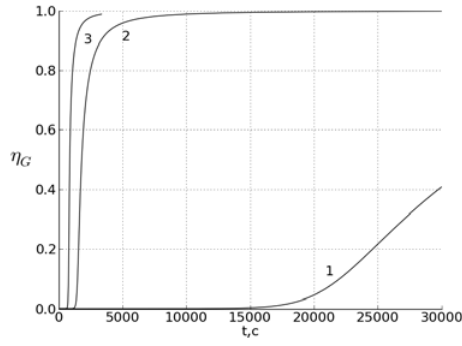
Figure 2. Dynamics of gaseous product share at varying potential (values are taken in the vicinity of the electrode). $1 - \varphi = 20000$ B., $2 - \varphi = 30000$ B., $3 - \varphi = 35000$ B. $\varsigma = 0.25$, $f = 10\,\mathrm{kHz}$.
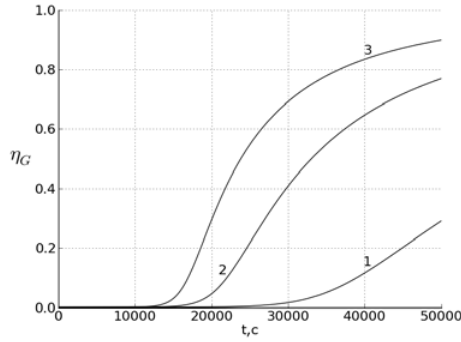

Figure 3. Dynamics of gaseous product share at varying porosity (values are taken in the vicinity of the electrode). $1 - \varsigma = 0.1$, $2 - \varsigma = 0.25$, $3 - \varsigma = 0.4$. $\varphi = 20000$ B., $f = 10\,\mathrm{kHz}$.

where c_g, ρ_g – gas heat capacity and density; $\Phi_g = \eta_G \sigma_2 E^2 + (1 - \eta_G)\varepsilon_2\varepsilon_0\Gamma E^2 tg\delta_2$ – heat source associated with the action of electromagnetic field on gas; σ_2 – conductivity, ε_2 – gas permittivity; $tg\delta_2$ – angle tangent (ratio) of dielectric losses; $\frac{d...}{dt} = \frac{\partial...}{\partial t} + v_x\frac{\partial...}{\partial x} + v_y\frac{\partial...}{\partial y}$, v_x, v_y – components of gas velocity vector $\boldsymbol{v}_g$.

Total gas phase reaction is exothermic and conforms to the following schema: $G_R \rightarrow G_p$. The proportion of gaseous reactant is changed by the following law:

$$\frac{d\eta_G}{dt} = -k_2\eta_G \exp\left(-\frac{E_2}{RT_g}\right) v_G + \frac{\alpha_m}{\varsigma}\left(\eta_{BG} - \eta_G\right)$$

where k_2 – pre-exponential factor; E_2 – activation energy of the gaseous phase reaction; v_G – stoichiometric coefficient, $\frac{d...}{dt} = \frac{\partial...}{\partial t} + v_x\frac{\partial...}{\partial x} + v_y\frac{\partial...}{\partial y}$.

Equation for condition of a gas, which could not be regarded as perfect, in the first approximation is as follows:

$$dp_g = K_T\left(\alpha_T dT_g + \alpha_G d\eta_g\right),$$

where p_g – gas pressure; K_T – volumetric isothermal elastic module, α_T – coefficient of thermal expansion, α_T – concentration expansion factor.

Gas velocity was calculated by the Darcy's law:

$$\boldsymbol{v}_g = -K_f\nabla p_g,$$

where $K_f = \frac{K}{\eta}$, K – coefficient of filtration, η – dynamic viscosity, whence it follows:

$$\boldsymbol{v}_g = -K_f K_T \left(\alpha_T \nabla T + \alpha_G \nabla \eta_G\right).$$

The problem is solved numerically by using an implicit scheme of splitting by coordinates and coordinate-wise run.

Example of calculation for gaseous product accumulation is shown in Figs. 2, 3:

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