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VERIFICATION OF THE MATHEMATICAL MODEL OF THE MASS FLOW RATE OF MOIST BULK MATERIALS FOR CONCRETE MIXING PLANT FEEDING SYSTEMS

pages 6–11

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The object of this research is a mathematical model of mass flow rate of moist bulk materials (construction sand) in feeding systems of concrete mixing plants (CMPs). The subject of the research is the experimental verification of this mathematical model under real production conditions.

The problem addressed concerns the critical instability of mass flow rate when using natural washed sand. Increased moisture content (6–10%) changes the mass flow regime to a funnel flow and causes the formation of arches above the discharge opening. The coefficient of variation in dosing under such conditions reaches 12–25%, which is 4–8 times higher than the state standard for accuracy.

The mathematical model was verified using results obtained on a real CMP with a capacity of 60 m^3/h, designed and commissioned by the authors and still in operation today. They confirm that installing an active loosener with a rotational speed of $\omega_{pr} \geq 2.5 \cdot \omega_{cr}$ completely solves the problem of stabilizing the dosage across the entire range of production moisture contents. Threshold rotational speeds have been established depending on moisture content (specifically, 87 rpm for 6%). A constructed three–dimensional response surface demonstrates that, for a guaranteed dosing error of ≤3%, the working speed of the loosener must be 2.5 times higher than the threshold. Adherence to this operating mode reduces the actual variation to 1.8%. A mathematical model of mass flow rate ($R^2 = 0.963$) was also statistically described, and empirical coefficients were determined: pin resistance in the material (1.12) and mechanism efficiency (2.8).

This effect is explained by the artificial, abrupt transition of the material from a vortex flow regime back to a bulk flow regime. Upon reaching the critical rotation speed of the pins, the capillary bonds between the grains are intensively broken, thereby reducing the effective angle of internal friction and completely eliminating stagnant zones in the hopper. All of this instantly restores stable, continuous gravitational flow.

The results are practically applicable to the engineering calculation of feeding systems for concrete mixing plants and can be adapted for related industrial sectors.

Keywords: concrete mixing plant, loosener, moist sand, dosing stabilization, mathematical model, verification.

References

1. Janssen, H. A. (1895). Versuche über Getreidedruck in Silozellen. *Zeitschrift des Vereines Deutscher Ingenieure, 39*, 1045–1049. Available at: https://blog.espe-bretagne.fr/ktiblog/wp-content/uploads/2013/12/Janssen1895.pdf
2. Johanson, J. R. (1964). Stress and Velocity Fields in the Gravity Flow of Bulk Solids. *Journal of Applied Mechanics, 31 (3),* 499–506. https://doi.org/10.1115/1.3629668
3. Jenike, A. W. (1964). Storage and Flow of Solids. *Bulletin of the University of Utah, 53 (26).* Available at: https://digital.library.unt.edu/ark:/67531/metadc1067072/m1/1/
4. Nedderman, R. M. (1992). *Statics and Kinematics of Granular Materials.* Cambridge: Cambridge University Press. https://doi.org/10.1017/cbo9780511600043
5. Schulze, D. (2008). *Powders and Bulk Solids: Behavior, Characterization, Storage and Flow.* Berlin: Springer, 512. https://doi.org/10.1007/978-3-540-73768-1
6. Rhodes, M. (Ed.) (2008). *Introduction to Particle Technology.* Wiley. https://doi.org/10.1002/9780470727102
7. ISO 5725-1:2023. Accuracy (trueness and precision) of measurement methods and results. Part 1: General principles and definitions (2023). *International Organization for Standardization.* Available at: https://www.iso.org/standard/69418.html
8. ISO/IEC 17025:2017. General requirements for the competence of testing and calibration laboratories (2017). *International Organization for Standardization.* Available at: https://www.iso.org/standard/66912.html
9. *DSTU B V.2.7-175:2008. Building materials. GUIDE ON THE USE OF CHEMICAL ADMIXTURES TO CONCRETES AND MORTARS.* (2010). Kyiv: Minrehionbud Ukrayiny. Available at: https://ybeton.od.ua/wp-content/uploads/%D0%94%D0%A1%D0%A2%D0%A3-%D0%9D-%D0%91-%D0%92.2.7-1752008.-%D0%91%D1%83%D0%B4%D1%96%D0%B2%D0%B5%D0%BB%D1%8C%D0%BD%D1%96-%D0%BC%D0%B0%D1%82%D0%B5%D1%80%D1%96%D0%B0%D0%BB%D0%B8.-%D0%9D%D0%B0%D1%81%D1%82%D0%B0%D0%BD%D0%BE%D0%B2%D0%B0-%D1%89%D0%BE%D0%B4%D0%BE-%D0%B7%D0%B0%D1%81%D1%82%D0%BE%D1%81%D1%83%D0%B2%D0%B0%D0%BD%D0%BD%D1%8F-%D1%85%D1%96%D0%BC%D1%96%D1%87%D0%BD%D0%B8%D1%85-%D0%B4%D0%BE%D0%B1%D0%B0%D0%B2%D0%BE%D0%BA-%D1%83-%D0%B1%D0%B5%D1%82%D0%BE%D0%BD%D0%B0%D1%85-%D1%96-%D0%B1%D1%83%D0%B4%D1%96%D0%B2%D0%B5%D0%BB%D1%8C%D0%BD%D0%B8%D1%85-%D1%80%D0%BE%D0%B7%D1%87%D0%B8%D0%BD%D0%B0%D1%85.pdf
10. *DSTU B V.2.7-96-2000. Building materials Ready-mixed concrete. Specifications.* (2000). Kyiv: Derzhbud Ukrayiny. Available at: https://ybeton.od.ua/wp-content/uploads/2015/04/%D0%94%D0%A1%D0%A2%D0%A3-%D0%91-%D0%92.2.7-96-2000.pdf
11. Levchenko, O., Korobko, B. (2024). Optimization of the concrete production process in terms of energy consumption. *Technology Audit and Production Reserves, 6 (1 (80)),* 11–15. https://doi.org/10.15587/2706-5448.2024.319827
12. Petruniak, M., Rubel, V., Chevhanova, V., Kulakova, S. (2021). Application of grout slurries with the defecate addition for effective well cementing. *Mining of Mineral Deposits, 15 (1),* 59–65. https://doi.org/10.33271/mining15.01.059

MECHANICS

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GAINING A DEEPER UNDERSTANDING OF THE BEHAVIOR OF SOIL MIXING UNDER THE AGING EFFECT BY COMPARING PREDICTIVE APPROACH AND PRACTICAL RESULTS

pages 12–18

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The object of this research is the behavior of soil mixing column.

The problem that this research aims to address is to better understand the behavior of soil mixtures under the effect of wetting-drying cycles (aging) and its impact on unconfined compressive strength.

The research consists of a parametric laboratory (experimental) research, with the preparation of different mixtures containing varying percentages of fine particles, cement, and water/cement (W/C) ratios. Eight different formulations were studied: a reference formulation, three formulations with 25% fine particles and different cement dosages, three formulations with 10% fine particles, and two with 5% fine particles. A reference sample was used to track the evolution of these results. This variation in mixture composition allows to observe the influence of particle size distribution, clay content, and cement content on the relative unconfined compressive strength of the prisms. The results show that the relative compressive strength of the prisms decreases by approximately 41% between 3 and 24 cycles, regardless of the cement content. It increases by 18 to 25% with increasing cement content for all formulations, but decreases by approximately 23% with increasing fine particle content. This research allowed to propose an equation to predict the evolution of relative compressive strength as a function of time, the number of wetting-drying cycles, cement content, and fine particle content. The various results obtained highlight the influence of fine particle and cement content on the performance and durability of soil mixing columns, and underscore the importance of conducting a thorough parametric research in the laboratory to facilitate the efficient and economical design of these columns.

Keywords: fine particles, soil-mixing, durability, damage, aging cycle, compressive strength, cement dosage.

References

1. Terashi, M. (2003). The State of Practice in Deep Mixing Methods. *Grouting and Ground Treatment,* 25–49. https://doi.org/10.1061/40663(2003)2
2. Denies, N., Huybrechts, N. (2017). Deep mixing method for the construction of earth and water retaining walls. *RILEM Technical Letters, 2,* 1–9. https://doi.org/10.21809/rilemtechlett.2017.27
3. Tinoco, J., Gomes Correia, A., Cortez, P. (2014). Support vector machines applied to uniaxial compressive strength prediction of jet grouting columns. *Computers and Geotechnics, 55,* 132–140. https://doi.org/10.1016/j.compgeo.2013.08.010
4. Topolnicki, M., Soltys, G. (2012). Novel Application of Wet Deep Soil Mixing for Foundation of Modern Wind Turbines. *Grouting and Deep Mixing 2012,* 533–542. https://doi.org/10.1061/9780784412350.0039
5. Moseley, M. P., Kirsch, K. (Eds.). (2004). *Ground Improvement.* https://doi.org/10.1201/9780203489611
6. Tinoco, J., Gomes Correia, A., Cortez, P. (2011). Application of data mining techniques in the estimation of the uniaxial compressive strength of jet grouting columns over time. *Construction and Building Materials, 25 (3),* 1257–1262. https://doi.org/10.1016/j.conbuildmat.2010.09.027
7. Kamdem, A., Elat, E., Eslami, J., Amba, J. C., Sali, M., Mbessa, M., Noumowé, A. (2024). Influence of the Nature of Cement on the Physical and Mechanical Properties of Soil Concretes from Sandy Clay and Laterite. *CivilEng, 5 (2),* 307–326. https://doi.org/10.3390/civileng5020016
8. *Rapport de sol N°056/2012.* Elaboré par Laboratoire de l'Habitat de Construction de l'Est, 6–22. Available at: https://lnhc-dz.com
9. Helson, O., Beaucour, A.-L., Eslami, J., Noumowe, A., Gotteland, P. (2017). Physical and mechanical properties of soilcrete mixtures: Soil clay content and formulation parameters. *Construction and Building Materials, 131*, 775–783. https://doi.org/10.1016/j.conbuildmat.2016.11.021
10. Design of experiments. *Moresteam.* Available at: https://www.moresteam.com/toolbox/design-of-experiments

METALLURGICAL TECHNOLOGY

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DEVELOPMENT OF FAST SPHEROIDIZING ANNEALING MODES AND MODELING OF THE INTENSIFICATION PROCESS OF CEMENTITE SPHEROIDIZATION OF LOW-CARBON STEELS

pages 19–26

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The object of research is the process of cementite spheroidization of 20Г2Р low-carbon steel during heat treatment, in particular spheroidizing annealing. Special attention in conducting research is paid to the influence of the initial structural state of the steel, temperature regimes and heating methods on the formation of the microstructure of the workpiece.

Traditional methods of spheroidizing annealing are characterized by a significant duration of the regime, which reaches more than 10 hours and, in connection with this, energy costs, which limits the efficiency of the technological process. This is especially true for low-carbon steels with a relatively weak thermodynamic stimulus for spheroidization.

The research problem is the need to reduce the duration of spheroidizing annealing of steel and reduce energy costs while ensuring a uniform distribution of cementite globules in the ferrite matrix.

The scientific novelty of the obtained results lies in the development of high-speed regimes of spheroidizing annealing of 20Г2Р steel using the initial ferritic-bainite structure and non-isothermal holding with increasing temperature, in contrast to known studies based on long isothermal holdings. It is shown that the total duration of spheroidizing annealing of low-carbon steels significantly depends on the initial structural state of the workpiece. It is established that the transition from ferritic-pearlitic to ferritic-bainite initial structural state provides a reduction in the duration of cementite spheroidization from 1500–1800 s to 200–450 s.

The features of the intensification of spheroidizing annealing of low-carbon steels have been studied and the influence of changes in the values of thermodynamic and kinetic factors during structural transformation has been established. The effectiveness of using non-isothermal holding with increasing temperature in a certain temperature range and optimization of spheroidizing treatment parameters has been proven.

The practical significance of the results obtained lies in the implementation of the developed high-speed modes of spheroidizing annealing of 20Г2Р low-carbon steel for the production of coiled strip and wire with a diameter of 6.0–20.0 mm. The obtained structural states of the blanks provide the necessary set of properties for the subsequent manufacture of metal products by cold drawing, in particular products of complex configuration. The proposed approaches are fully suitable and meet the requirements for technological and mechanical properties of blanks for the manufacture of metal products by cold drawing.

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Keywords: spheroidization, thermodynamics, kinetics, structural transformations, non-isothermal holding, microstructure, process modeling.

References

1. Christian, J. W. (2002). *The Theory of Transformations in Metals and Alloys.* Oxford: Pergamon Press, 1200. https://doi.org/10.1016/b978-0-08-044019-4.x5000-4
2. Dolzhenkov, I. Ye. (2011). Shliakhy suttievoho skorochennia chasu (tryvalosti) ta pokrashchennia yakosti sferoidyzatsii karbidiv stalevoi metaloproduktsii. *Budivnytstvo, materialoznavstvo, mashynobudivnytstvo, 58,* 262–267. Available at: http://nbuv.gov.ua/UJRN/smmsc_2011_58_39
3. Ivashchenko, V. P., Shvachych, H. H., Sobolenko, M. O., Hul, Yu. P., Sobolenko, O. V., Kokashynska, H. V., Moroz, D. M. (2020). Pat. No. 143971 UA. *Ustanovka dlia intensyfikatsii sferoidyzuiuchoho vidpaliuvannia stali.* MPK C21D 1/26 (2006.01). No. u202000940; declareted: 14.02.2020; published: 25.08.2020, Bul. No. 16. Available at: https://sis.nipo.gov.ua/media/UTILITY_MOD/2020/u202000940/published_description.pdf?utm_source
4. Nasiri, Z., Mirzadeh, H. (2019). Spheroidization heat treatment and intercritical annealing of low carbon steel. *Journal of Mining and Metallurgy, Section B: Metallurgy, 55 (3),* 405–411. https://doi.org/10.2298/jmmb180813033n
5. Zhuchkov, S. M., Baryshev, E. V., Lokhmatov, O. P., Lutsenko, V. O., Kliuchnikov, K. Yu. (2009). Creation of energy saving and ecologically pure metal preparation site for cold deformation in the shapes of simple and complex sections. *Nauka ta innovatsii, 6 (5),* 36–47. Available at: http://scinn.org.ua/sites/default/files/pdf/2009/N6/Zjuchkov.pdf
6. Hul, Yu. P., Sobolenko, M. O. (2012). Osnovy shvydkisnoi sferoidyzatsii tsementytu v nyzkovuhletsevykh staliakh dlia kholodnoi vysadky. *Construction, materials science, mechanical engineering, 64,* 128–136. Available at: http://smm.pgasa.dp.ua/article/view/63052
7. Kaputkin, D. E. (2005). Correlation between the thermokinetic parameters of difusional decomposition and the activation energy of difusion in steels and nonferrous alloys. *Physics of Metals and Metallography, 4 (99),* 343–347. Available at: https://www.researchgate.net/publication/289844078_Correlation_between_the_thermokinetic_parameters_of_diffusional_decomposition_and_the_activation_energy_of_diffusion_in_steels_and_nonferrous_alloys =
8. DSTU 3684-98. *Prokat iz yakisnoi konstruktsiinoi nelehovanoi ta lehovanoi stali dlia kholodnoho vydavliuvannia ta vysadzhuvannia.* Tekhnichni umovy. (ISO 4954-93). (2022). Kyiv: Derzhavnyi standart Ukrainy, 16.
9. Brown, M. E., Gallagher, P. K. (2003). *Handbook of Thermal Analysis and Calorimetry. Vol. 2. Applications to Inorganic and Miscellaneous Materials.* Amsterdam: Elsevier, 905. Available at: https://www.sciencedirect.com/handbook/handbook-of-thermal-analysis-and-calorimetry/vol/2/suppl/C
10. Gul, Yu. P., Sobolenko, M. A. (2024). Investigation of the patterns of structure formation and mechanical properties of steels during heat treatment. *Ukrainian Journal of Civil Engineering and Architecture, 6 (24),* 64–69. https://doi.org/10.30838/ujcea.2312.271224.64.1112
11. Sobolenko, M. O., Alieksieiev, M. O. (2024). Investigation of the influence of technological parameters on the kinetics of austenite decomposition in boron-containing steel. *Zbirnyk naukovykh prats NHU, 78,* 217–224. http://doi.org/10.33271/crpnmu/78.217
12. Python Software Foundation. *Python Programming Language.* Available at: https://www.python.org
13. Okonogi, M., Yamazaki, K. (2017). Development of Medium Carbon Steel Wire Rods for Cold Heading by Isothermal Transformation Treatment. *Nippon Steel and Sumitomo Metal Technical Report, 116,* 65–70. Available at: https://www.nipponsteel.com/en/tech/report/nssmc/pdf/116-13.pdf
14. Hauserova, D., Dlouhy, J., Novy, Z. (2014). Accelerated carbide spheroidisation and Refinement (ASR) of the C45 Steel during Controlled Rolling. *Materials and technology, 48 (5),* 797–800. Available at: https://www.researchgate.net/publication/282726155_Accelerated_carbide_spheroidisation_and_refinement_ASR_of_the_C45_steel_during_controlled_rolling
15. Vakulenko, I. O. (2008). Structural changes in carbon steel for a long exposures at subcritical temperatures. *Science and Transport Progress, 21,* 263–265. https://doi.org/10.15802/stp2008/15829

TECHNOLOGY AND SYSTEM OF POWER SUPPLY

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AN INTEGRATED ASSESSMENT OF GEOMECHANICAL AND ENERGY PARAMETERS FOR DEEP PIT RECLAMATION VIA REGENERATIVE CONVEYORS: A KRYVYI RIH CASE STUDY

pages 27–33

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The object of research is the technological process of rock mass handling. During active mining, this process required moving the overburden from the pit to surface terrain dumps. Once extraction was completed, the operation shifted to mine reclamation through in-pit dumping. At that stage, the stored rock mass was relocated from external dumps back into the mined-out space using regenerative conveyor systems. The main problem to be solved involved reducing the energy footprint of such reclamation operations without sacrificing the geomechanical stability of the dump slope. Conventional haulage methods relied heavily on fossil fuels, leading to carbon emissions and high operating costs. This economic and environmental burden demanded a shift toward technologies capable of capturing the gravitational potential energy of the relocated rock mass.

The research combined limit equilibrium analysis for slope stability evaluation with numerical modeling of the interconnected energy and geomechanical balance. To pinpoint exactly where gravity acted on each rock volume, a step-by-step vertical discretization of the benches was applied, coupled with the geometric centroid method.

Modeling of the reclamation system designed for a 500-meter-deep pit in Ukraine's Kryvyi Rih region proved that regenerative conveyors are capable of accumulating up to 542.36 million kWh of energy (1.24–1.34 kWh/m³). Calculations revealed a 6.9% technological gap from the theoretical limit. The centroid method yielded zero mathematical error, whereas the area bisection technique underestimated the energy potential by 11.7%.

These findings offered a practical framework for designing reclamation and decarbonization strategies at deep open-pit mines. By leveraging the patented technological solution (Ukrainian Patent No. 158796), mining operators could transform standard environmental cleanup operations into a revenue-generating energy asset.

Keywords: reclamation, open-pit, conveyor, regeneration, geomechanics, efficiency, dumping, recovery, decarbonization, modeling.

References

1. *Polozhennia pro proiektuvannia vnutrishnikh vidvaliv ta skladuvannia vyrobnychykh vidkhodiv u zalizorudnykh ta fliusovykh karierakh* (2004). Nakaz Ministerstva promyslovoi polityky Ukrainy No. 412. 17.08.2004. Available at: https://zakon.rada.gov.ua/laws/show/z1027-04
2. Drizhenko, A., Adamchuk, A., Tamouya, S., Telnov, V. (2018). Research of inside dump parameters in worked-out area of deep opencast mines. *Zbirnyk naukovykh prats Natsionalnoho hirnychoho universytetu, 53,* 56–65. Available at: http://nbuv.gov.ua/UJRN/znpngu_2018_53_8
3. Drizhenko, A. Yu. (2014). *Vidkryti hirnychi roboty.* Natsionalnyi hirnychyi universytet, 590.
4. Legwaila, I. A., Lange, E., Cripps, J. (2015). Quarry reclamation in england: a review of techniques. *Journal American Society of Mining and Reclamation, 4 (2),* 55–79. https://doi.org/10.21000/jasmr15020055
5. Antonik, V., Shtanko, L., Antonik, I., Ivachenko, V. (2022). New technology of reclamation of slopes of waste and excavated rocks of mines and quarries. *IOP Conference Series: Earth and Environmental Science, 1049 (1),* 12003. https://doi.org/10.1088/1755-1315/1049/1/012003
6. Chelopo, D., Gupta, K. (2025). Exploring the Economic Hypothetical for Downhill Belt Conveyors Equipped with Three-Phase Active Front-End Load Converters. *Technologies, 13 (5),* 185. https://doi.org/10.3390/technologies13050185
7. Semenchenko, A., Stadnik, M., Belytsky, P., Semenchenko, D. (2018). The increase of the belt conveyors energy efficiency in intensive mining conditions. *Journal of Donetsk Mining Institute, 2,* 91–106. https://doi.org/10.31474/1999-981x-2018-2-91
8. Kawalec, W., Król, R., Suchorab, N. (2020). Regenerative Belt Conveyor versus Haul Truck-Based Transport: Polish Open-Pit Mines Facing Sustainable Development Challenges. *Sustainability, 12 (21),* 9215. https://doi.org/10.3390/su12219215
9. Kawalec, W., Król, R. (2021). Generating of Electric Energy by a Declined Overburden Conveyor in a Continuous Surface Mine. *Energies, 14 (13),* 4030. https://doi.org/10.3390/en14134030
10. Bolotnikov, A. V., Brovko, D. V., Romanenko, A. O., Romanenko, O. V., Demchenko, D. A. (2025). Pat. No. 158796. *Sposib rekultyvatsii vidpratsovanykh kariеriv.* MKP E 21C 41/00, E 21C 41/32. No. u202404117; declareted: 19.08.2024; published: 20.03.2025, Bul. No. 12.

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IMPROVING THE DEVELOPMENT PROCESS OF TWO HYDRODYNAMICALLY ISOLATED LAYERS WITH DIFFERENT PERMEABILITIES UNDER JOINT DEVELOPMENT CONDITIONS USING A SINGLE WELL GRID

pages 34–42

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The object of research is the filtration processes observed in the process of joint development of two hydrodynamically isolated different permeability layers by a single well grid. The subject of research is the interaction of different permeability, hydrodynamically isolated layers (upper low permeability k_1 and lower high permeability k_2) in the process of development of a two-layer deposit in the presence of an impermeable membrane between the layers.

The research solved the problem of the influence of the permeability ratio on the final values of gas flow rates, layer pressure, gas recovery coefficients and the duration of the deposit development.

The work is aimed at studying the features of gas recovery from two different permeability layers with an impermeable membrane, which are developed by a single well grid.

During the research, the influence of the permeability ratio of the layers ($n = k_2/k_1$) of the two-layer deposit on the final gas recovery coefficient was determined. It was established that with an increase in the value of n, the high permeability layer is depleted more intensively and is disconnected from development faster. Thus, at the final stage of development for $n = 10$ in a high-permeability layer, the layer pressure is 3.00 MPa, and in a low-permeability layer – 4.77 MPa. The gas recovery coefficient for a low-permeability layer for $n = 10$ is only 83.94%, and for a high-permeability layer – 90.11%. Increasing gas recovery can be achieved by transferring wells to simultaneous-separate operation at a certain stage of development, by carrying out treatments of bottomhole zones of low-permeability layers.

The results obtained can be effectively used in the joint development of two hydrodynamically isolated different-permeability layers with joint development by a single well grid. This allows to increase the gas recovery coefficient and the efficiency of further development of two different-permeability layers with an impermeable membrane.

Keywords: field, modeling, permeability, gas recovery coefficient, layer pressure, gas flow rate, impermeable membrane.

References

1. Kondrat, R. M., Kondrat, O. R. (2017). Prohnozuvannia tekhnolohichnykh pokaznykiv rozrobky dvoplastovoho hazovoho rodovyshcha v umovakh hazovoho rezhymu spilnoiu sitkoiu sverdlovyn za postiinoho debitu hazu. *Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch, 2,* 7–12. Available at: http://nbuv.gov.ua/UJRN/rrngr_2017_2_2
2. Kondrat, O. R. (2015). Enhancement of efficiency for further development of a depleted gas condensate fields. *Heotekhnichna mekhanika, 122.* Available at: https://www.geotm.dp.ua/attachments/article/2904/17.pdf
3. Kondrat, R., Dremliukh, N., Kondrat, O., Matiishyn, L. (2023). Determination of predictive technological indicators for the development of a two-seam gas field in the gas mode by a common well grid and their operation with constant wellhead pressure. *Prospecting and Development of Oil and Gas Fields, 3,* 34–41. https://doi.org/10.69628/pdogf/3.2023.34
4. Kondrat, R., Matiishyn, L. (2022). Improving the efficiency of production wells at the final stage of gas field development. *Mining of Mineral Deposits, 16 (2),* 1–6. https://doi.org/10.33271/mining16.02.001
5. Lefkovits, H. C., Hazebroek, P., Allen, E. E., Matthews, C. S. (1961). A Study of the Behavior of Bounded Reservoirs Composed of Stratified Layers. *Society of Petroleum Engineers Journal, 1 (1),* 43–58. https://doi.org/10.2118/1329-g
6. Fetkovlch, M. J., Bradley, M. D., Works, A. M., Thrasher, T. S. (1990). Depletion Performance of Layered Reservoirs Without Crossflow. *SPE Formation Evaluation, 5 (3),* 310–318. https://doi.org/10.2118/18266-pa
7. El-Banbi, A. H., Wattenbarger, R. A. (1996). Analysis of Commingled Tight Gas Reservoirs. *SPE Annual Technical Conference and Exhibition.* Denver. https://doi.org/10.2118/36736-ms
8. Kuppe, F., Chugh, S., Connell, P. (2000). Material Balance for Multi-Layered, Commingled, Tight Gas Reservoirs. *SPE/CERI Gas Technology Symposium.* Calgary. https://doi.org/10.2118/59760-ms
9. Hedong, S., Yujin, W., Shimin, Z., Liangren, L. (2008). Discussion on Dynamic Reserves Estimation of Multilayer Gas Reservoir With Material Balance Method. *CIPC/SPE Gas Technology Symposium 2008 Joint Conference.* Calgary. https://doi.org/10.2118/113665-ms
10. Yujin, W., Yong, H. (2015). The Key Factors Affecting the Deliverability and OGIP of Multi-layer Gas Reservoirs. *Abu Dhabi International Petroleum Exhibition and Conference.* https://doi.org/10.2118/177647-ms
11. Juell, A., Whitson, C. H. (2011). Backpressure Equation for Layered Gas Reservoirs. *SPE Annual Technical Conference and Exhibition.* Denver. https://doi.org/10.2118/146066-ms

12. Fetkovich, M. J., Ebbs, D. J., Voelker, J. J. (1994). Multiwell, Multilayer Model To Evaluate Infill-Drilling Potential in the Oklahoma Hugoton Field. *SPE Reservoir Engineering, 9 (3),* 162–168. https://doi.org/10.2118/20778-pa
13. Artun, E., Canbolat, S., Yildirim, E. C., Acikgoz, C., Yuruker, O. (2024). An Integrated Workflow for Data Analytics-Assisted Reservoir Management with Incomplete Well Log Data. *SPE Journal, 30 (2),* 486–506. https://doi.org/10.2118/223633-pa
14. Kondrat, R. M., Kondrat, O. R., Matiishyn, L. I. (2023). *Rozrobka ta ekspluatatsiia hazovykh i hazokondensatnykh rodovyshch.* Ivano-Frankivsk: FOLIANT, 568.

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DEVELOPMENT OF A MATHEMATICAL MODEL FOR GAS HYDRATE SYNTHESIS AND DISSOCIATION PROCESSES IN A GAS PIPELINE UNDER MICROWAVE RADIATION

pages 43–49

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The object of research is the heat and mass transfer processes that occur on the surface of a gas hydrate granule moving in a gas pipeline.

The research solved the problem of the oil and gas industry – the fight against the formation of gas hydrates (GH) in hydrocarbon production and transportation systems. A promising approach to the intensification of hydrate dissociation by using microwave electromagnetic radiation is proposed. The features of the results obtained consist in the development of a mathematical model that combines two processes of synthesis and dissociation of gas hydrates, taking into account hydrodynamic processes in the pipeline. The main differences of the proposed mathematical model are: simultaneous consideration of two mutually opposing processes of synthesis and dissociation of gas hydrate on the surface of the granule; these processes occur during the movement of the gas hydrate granule inside the gas pipeline; heating of the gas hydrate granule occurs as a result of its absorption of direct and reflected multimode microwave electromagnetic radiation.

A complex approximation dependence was obtained for determining the required emitter power $P_w = 124C_{gh}/R^{1.7}$, which allows one to quickly calculate the required minimum magnetron power to combat hydrate formation.

It was established that for the destruction of small particles (<0.01 mm) even if their concentration is low (0.01–0.02%), a relatively high-power emitter (3–5 kW) is required. The same was observed in the case of GH accumulation to high concentrations (>0.1%) with particle sizes of 0.05–0.1 mm. Therefore, the most advantageous strategy for combating GH accumulation is its active destruction when it reaches sizes of 0.02–0.05 mm, which do not harm the course of the main technological process.

The obtained dependences are the basis for improving gas preparation technologies under hydrate formation conditions by using microwave radiation energy.

Keywords: gas hydrates, ultrahigh-frequency electromagnetic radiation, dissociation, mathematical modeling, gas pipeline, energy efficiency, heat balance.

References

1. Dmytrenko, V. I., Zezekalo, I. G., Vynnykov, Y. L. (2022). The use of bischofite in the gas industry as an inhibitor of hydrate formation. *IOP Conference Series: Earth and Environmental Science, 1049 (1),* 12052. https://doi.org/10.1088/1755-1315/1049/1/012052
2. Pedchenko, M. M.; Biletskyi, V. S. (Ed.) (2014). *Hidratoutvorennia vuhlevodnevykh haziv.* Poltava: PoltNTU, 182. Available at: https://www.researchgate.net/publication/338117028_Pedcenko_MM_Gidratoutvorenna_vuglevodnevih_gaziv_monografia_MM_Pedcenko_za_red_VS_Bileckogo_-_Poltava_PoltNTU_2014_-_182_s_ISBN_978-966-616-129-4
3. Dmytrenko, V., Podoliak, T. (2024). Research of methanol content in technological flows of facilities that process gas preparation by low-temperature separation method. *Technology Audit and Production Reserves, 6 (1 (80)),* 46–53. https://doi.org/10.15587/2706-5448.2024.318926
4. Sloan, E. D. (1998). *Clathrate hydrates of natural gases.* Marcel Dekker. Available at: https://www.abebooks.com/9780824799373/Clathrate-Hydrates-Natural-Gases-Second-0824799372/plp
5. Li, D.-L., Liang, D.-Q., Fan, S.-S., Li, X.-S., Tang, L.-G., Huang, N.-S. (2008). In situ hydrate dissociation using microwave heating: Preliminary study. *Energy Conversion and Management, 49 (8),* 2207–2213. https://doi.org/10.1016/j.enconman.2008.01.031
6. Dreus, A. Y., Bondarenko, V. I., Biletskyi, V., Lysenko, R. (2020). Mathematical simulation of heat and mass exchange processes during dissociation of gas hydrates in a porous medium. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5,* 33–39. https://doi.org/10.33271/nvngu/2020-5/033
7. Rebai, N., Hadjadj, A., Benmounah, A., Berrouk, A. S., Boualleg, S. M. (2019). Prediction of natural gas hydrates formation using a combination of thermodynamic and neural network modeling. *Journal of Petroleum Science and Engineering, 182,* 106270. https://doi.org/10.1016/j.petrol.2019.106270
8. Fatykhov, M. A., Akchurina, V. A., Stolpovsky, M. V. (2020). Numbrigal simulation of a thermodynamic process to decompose gas hydrate in a gas production well using, radiofrequency electromagnetic radiation. *IOP Conference Series: Materials Science and Engineering, 862 (6),* 62075. https://doi.org/10.1088/1757-899x/862/6/062075
9. Shi, M., Yang, L., Gao, S., Wang, G. (2022). Small-Diameter Tube Wall Damage-Detection Method Based on TE01 Mode Microwave. *Sensors, 22 (17),* 6476. https://doi.org/10.3390/s22176476
10. Yang, H., Liu, X., Yue, J., Tang, X. (2022). Analysis of factors affecting microwave heating of natural gas hydrate combined with numerical simulation method. *Petroleum, 8 (3),* 391–402. https://doi.org/10.1016/j.petlm.2021.12.003
11. Bera, A., Babadagli, T. (2017). Effect of native and injected nano-particles on the efficiency of heavy oil recovery by radio frequency electromagnetic heating. *Journal of Petroleum Science and Engineering, 153,* 244–256. https://doi.org/10.1016/j.petrol.2017.03.051
12. Kutnyi, B., Pavlenko, A., Cherednikova, O. (2023). Theoretical Foundations of Gas Hydrate Synthesis Intensification. *Environmental and Climate Technologies, 27 (1),* 666–682. https://doi.org/10.2478/rtuect-2023-0049
13. Zhang, X., Wang, Y., Wang, H., Fan, S., Meng, X., Xu, H. (2024). Structural parameters optimization of microwave radiation antenna in hydrate reservoir based on multiphysical coupling model. *Case Studies in Thermal Engineering, 64,* 105449. https://doi.org/10.1016/j.csite.2024.105449
14. Dreus, A. Y., Gubin, O. I., Bondarenko, V. I., Liu, B., Batuta, V. I. (2022). Numerical study of microwave impact on gas hydrate plugs in a pipeline. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 4,* 28–33. https://doi.org/10.33271/nvngu/2022-4/028
15. Runborg, O. (2007). Mathematical models and numerical methods for high frequency waves. *Communications in Computational Physics, 2 (5),* 827–880. Available at: https://www.csc.kth.se/~olofr/Publications/runborg-cicp.pdf
16. Gear, C. W. (1971). *Numerical initial value problems in ordinary differential equations.* Prentice-Hall. Available at: https://www.scribd.com/doc/28941688/Numerical-Initial-Value-Problems-in-Ordinary-Differential-Equations#google_vignette
17. Abu-Nab, A. K., Koldoba, A. V., Koldoba, E. V., Poveshchenko, Y. A., Podryga, V. O., Rahimly, P. I., Bakeer, A. E. (2023). On the Theory of Methane Hydrate Decomposition in a One-Dimensional Model in Porous Sediments: Numerical Study. *Mathematics, 11 (2),* 341. https://doi.org/10.3390/math11020341

ELECTRICAL ENGINEERING AND INDUSTRIAL ELECTRONICS

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DEVELOPMENT OF MATHEMATIC MODEL OF ELECTRON ENERGY TRANSPORT IN ELECTRIC PROPULSION DEVICES WITH CLOSED ELECTRON DRIFT

pages 50–55

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The object of research is a physical process of the electron energy transport in electric propulsion devices with closed electron drift. Such devices include ionization chambers of plasma-ion thrusters, Hall effect thrusters, helicon thrusters, and high-frequency plasma, ions and electrons sources where electron-electron collisions free path is small compared to the channel width. This means that the electron velocity distribution function cannot be considered as Maxwell.

The height of the potential barrier in the boundary bipolar layer and the average electrons energies removed from the plasma should be solved as a kinetic one. The presence of a potential barrier also means that only electrons with energies greater than the barrier height participate in mass and energy transfer. The classical representation, which represents the entire spectrum, is therefore inapplicable.

This means that the results of the research must be used on the object, and this will enable the object to improve, i. e. the electron energy transport must be described by expression obtained in this research.

The above problem is solved in this work using the tools of a compromise kinetic-fluid model considering the presence of isotropy factors of electrons velocity projections distribution. It has been shown that the removal of mass and energy from the plasma is carried out only by electrons in a narrow spectral band, about half the electron temperature. The equations of the zero and first angular moments of the distribution function are written with an approximate notation for the radial-azimuth component of the second angular moment as a second-rank tensor. It is shown that the ratio of the energy and mass flux densities in the volume is almost the same as that at the boundary with the bipolar layer, which allows to close the equations system of the mathematical model of processes in electric propulsion devices with a closed electron drift. The obtained results can be applied in the case of subsonic electron flow, which is typical for plasma of all types of electric propulsion devices.

Keywords: closed electron drift, potential barrier, velocity distribution function, electrons mass and energy flux.

References

1. Hahn, D. W., Özişik, M. N. (2012). *Heat Conduction.* John Wiley & Sons. https://doi.org/10.1002/9781118411285
2. Torvén, S.; Palmadesso, P. J., Papadopoulos, K. (Eds.) (1979). Formation of Double Layers in Laboratory Plasmas. *Wave Instabilities in Space Plasmas.* Dordrecht: Springer, 109–128. https://doi.org/10.1007/978-94-009-9500-0_9
3. Hofer, R., Katz, I., Mikellides, I., Gamero-Castano, M. (2006). Heavy Particle Velocity and Electron Mobility Modeling in Hybrid-PIC Hall Thruster Simulations. *42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit.* https://doi.org/10.2514/6.2006-4658
4. Lopez Ortega, A., Mikellides, I. G. (2023). 2D Fluid-PIC Simulations of Hall Thrusters with Self-Consistent Resolution of the Space-Charge Regions. *Plasma, 6 (3),* 550–562. https://doi.org/10.3390/plasma6030038
5. Panelli, M., Morfei, D., Milo, B., D'Aniello, F. A., Battista, F. (2021). Axisymmetric Hybrid Plasma Model for Hall Effect Thrusters. *Particles, 4 (2),* 296–324. https://doi.org/10.3390/particles4020026
6. Nesterenko, S., Zhihao, H., Roshanpour, S. (2025). Compromise kinetic-fluid model of electrons dynamics in electric propulsion devices with closed electrons drift as an alternative to the hybrid PIC-Fluid method. *Aerospace Technic and Technology, 1,* 28–37. https://doi.org/10.32620/aktt.2025.1.03
7. Pitaevskii, L. P., Lifshitz, E. M. (1981). *Physical kinetics.* Butterworth-Heinemann, 461. Available at: https://dokumen.pub/qdownload/physical-kinetics.html
8. Fitzpatrick, R. (2016). *Plasma Fluid Theory.* University of Texas at Austin. Available at: https://farside.ph.utexas.edu/teaching/plasma/Plasma/Plasmahtml.html
9. Nesterenko, S., Roshanpour, S., Huang, Z. (2025). Mathematical aspects of M unlimited angular model in electric propulsion. *2nd International Scientific and Practical Conference "Challenges and Opportunities in Modern Scientific Research".* Ivano-Frankivsk, 208–213. Available at: https://isu-conference.com/wp-content/uploads/2025/07/Ivano-Frankivsk_Ukraine_23.04.25.pdf
10. Loyan, A. V., Nesterenko, S. Y., Zongshuai, G., Zhihao, H. (2021). Quasi-one-dimensional mathematical model of processes in Hall effect and plasma-ion thrusters. *Open Information and Computer Integrated Technologies, 92,* 41–54. https://doi.org/10.32620/oikit.2021.92.04
11. Guo, Z. (2021). Radial distribution of electrons rotation moment in hall effect and plasma-ion thrusters. *Aerospace Technic and Technology, 4,* 28–34. https://doi.org/10.32620/aktt.2021.4.04
12. Nesterenko, S., Huang, Z., Roshanpour, S. (2025). Parameters of the bipolar boundary layer in electric propulsion thrusters with closed electron drift: M1+ angular model. *2nd International Scientific and Practical Conference "Modern Scientific Research: Theoretical and Practical Aspects".* Riga: European Open Science Space, 462–479. Available at: https://www.eoss-conf.com/en/archive/modern-scientific-research-theoretical-and-practical-aspects-26-05-25/
13. Huang, Z. (2025). Electron dynamics in the Langmur layer in M-unlimited angular model in electric propulsion. *2nd International Scientific and Practical Conference "Achievements of Science and Applied Research".* Dublin: European Open Science Space, 231–239. Available at: https://www.eoss-conf.com/en/archive/achievements-of-science-and-applied-research-19-05-25/
14. Langmuir Probe System – Thruster Application (2021). *Impedans.* Available at: https://www.impedans.com/wp-content/uploads/2021/12/Langmuir_ThrusterApplication.pdf