Eastern-European Journal of Enterprise Technologies

jet.com.ua

EASTERN-EUROPEAN JOURNAL OF ENTERPRISE TECHNOLOGIES

ISSN 1729-3774

информационные технологии

інформаційні технології

information technologies

новая экономика

нова економіка

new economy

промышленные технологии

промислові технології

industrial applications

3/10 (99)
2019

Восточно-Европейский ЖУРНАЛ передовых технологий

Eastern-European Journal of Enterprise Technologies

Східно-Європейський ЖУРНАЛ передових технологій

▪ Ecology

3/10 (99) 2019

Content

ECOLOGY

6 Construction of a generalized model of the harmful substances biochemical destruction process kinetics under conditions of substrate inhibition using the methods of simulation modeling
G. Bakharieva, T. Falalieieva, S. Petrov, I. Mezentseva, B. Kobylianskyi, I. Tolkunov, O. Bondarenko

17 Use of fly ash for conditioning the excess activated sludge during deliquefaction at chamber-membrane filter presses
O. Zlatkovskyi, A. Shevchenko, T. Shevchenko

24 Design of fire-resistant heat- and soundproofing wood wool panels
Yu. Tsapko, D. Zavialov, O. Bondarenko, O. Pinchevs'ka, N. Marchenko, S. Guzii

32 Development of a method for optimization calculation of a group of sound-insulating panels for airborn noise protection
O. Mamontov, T. Stytsenko

38 Assessment and prevention of the propagation of carbon monoxide over a working area at arc welding
V. Berezutskyi, I. Hondak, N. Berezutska, V. Dmitrik, V. Gorbenko, V. Makarenko

49 Development of a highly efficient combined apparatus (a combination of vortex chambers with a bin) for dry dedusting of gases
I. Pitak, V. Shaporev, S. Briankin, B. Komarysta, D. Nechyporenko

56 Abstract&References

ГОЛОВНИЙ РЕДАКТОР

Дьомін Дмитро Олександрович
д. т. н., професор Національного технічного університету «Харківський політехнічний інститут»,
директор ПП «Технологічний Центр», Харків (Україна)

Терзіян Ваган Якович
д. т. н., професор Університету Ювяскюля (Фінляндія)

РЕДАКЦІЙНА КОЛЕГІЯ

ВИРОБНИЧО-ТЕХНОЛОГІЧНІ СИСТЕМИ

Awrejcewicz Jan, Professor of Lodz University of Technology, Lodz (Poland); **Korzhyk Volodymyr,** Doctor of Technical Sciences, Chinese-Ukrainian E. O. Paton Welding Institute (CUPWI), Guangzhou (China); **Marcin Kamiński,** Professor of Lodz University of Technology, Lodz (Poland); **Shen Houfa,** Professor of Tsinghua University, Beijing (China); **Ulusoy Uğur,** Professor of Cumhuriyet Universitesi, Sivas (Turkey); **Загірняк М. В.,** д. т. н., проф., Кременчуцький національний університет імені Михайла Остроградського, Кременчук (Україна); **Залога В. О.,** д. т. н., проф., Сумський державний університет, Суми (Україна); **Кіндрачук М. В.,** д. т. н., проф., Національний авіаційний університет, Київ (Україна)

ІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ. СИСТЕМИ УПРАВЛІННЯ В ПРОМИСЛОВОСТІ

Cardoso Jorge, Professor of University of Coimbra, Faculty of Science and Technology, Coimbra (Portugal); **Iyengar Sitharama Sitharama,** Professor of Florida International University, Miami, (USA); **Jakab Frantisek,** Associate Professor of Technical University of Kosice, Department of Computers and Informatics, Kosice (Slovak Republic); **Omelayenko Borys,** PhD, Senior Software Engineer at Elsevier Amsterdam Area, Amsterdam (Netherlands); **Terziyan Vagan,** Professor of University of Jyvaskyla, Department of Mathematical Information Technology, Jyvaskyla (Finland); **Wrycza Stanislaw,** Professor of Uniwersytet Gdanski, Gdańsk (Poland); **Жолткевич Г. М.,** д. т. н., проф., Харківський національний університет імені В. Н. Каразіна, Харків (Україна); **Лахно В. А.,** д. т. н., проф., Європейський університет, Київ (Україна); **Литвин В. В.,** д. т. н., проф., Національний університет «Львівська політехніка», Львів (Україна); **Остапов С. Е.,** д. ф.-м. н., проф., Чернівецький національний університет імені Юрія Федьковича, Чернівці (Україна); **Пелещишин А. М.,** д. т. н., проф., Національний університет «Львівська політехніка», Львів (Україна); **Теслюк В. М.,** д. т. н., проф., Національний університет «Львівська політехніка», Львів (Україна)

ПРОЦЕСИ УПРАВЛІННЯ

Rab Nawaz Lodhi, PhD, COMSATS Institute of Information Technology Sahiwal Campus (Pakistan); **Бутько Т. В.,** д. т. н., проф., Український державний університет залізничного транспорту, Харків (Україна); **Гогунський В. Д.,** д. т. н., проф., Одеський національний політехнічний університет, Одеса (Україна); **Дьомін Д. О.,** д. т. н., проф., Національний технічний університет «Харківський політехнічний інститут», директор ПП «Технологічний Центр», Харків (Україна); **Мямлін С. В.,** д. т. н., проф., Дніпропетровський національний університет залізничного транспорту, Дніпро (Україна); **Панченко С. В.,** д. т. н., проф., Український державний університет залізничного транспорту, Харків (Україна); **Прохорченко А. В.,** д. т. н., проф., Український державний університет залізничного транспорту, Харків (Україна); **Сіра О. В.,** д. т. н., проф., Національний технічний університет «Харківський політехнічний інститут», Харків (Україна)

МАТЕМАТИКА ТА КІБЕРНЕТИКА - ПРИКЛАДНІ АСПЕКТИ

Ahmad Izhar, Associate Professor of King Fahd University of Petroleum and Minerals, Department of Mathematics and Statistics, Dhahran (Saudi Arabia); **Hari Mohan Srivastava,** Professor University of Victoria, Department of Mathematics and Statistics, Victoria (Canada); **Kanellopoulos Dimitris,** PhD, University of Patras, Patra (Greece); **Trujillo Juan J.,** Professor of Universidad de la Laguna, Faculty of Mathematics, San Cristobal de La Laguna (Spain); **Weber Gerhard Wilhelm,** Professor of Middle East Technical University, Institute of Applied Mathematics, Ankara (Turkey); **Атаманюк І. П.,** д. т. н., проф., Миколаївський національний аграрний університет, Миколаїв (Україна); **Кондратенко Ю. П.,** д. т. н., проф., Чорноморський національний університет імені Петра Могили, Миколаїв (Україна); **Романова Т. Є.,** д. т. н., проф., Інститут проблем машинобудування ім. А. М. Підгорного НАН України, Харків (Україна); **Саваневич В. Є.,** д. т. н., проф., Державне космічне агентство України, Київ (Україна)

ПРИКЛАДНА ФІЗИКА

Bobitski Yaroslav, Professor of University of Rzeszow, Department of mechatronics, Rzeszów (Poland); **Machado Jose Antonio Tenreiro,** Professor of Polytechnic of Porto, Institute of Engineering, Department of Electrical Engineering (Portugal); **Magafas Lykourgos,** Professor of Eastern Macedonia & Thrace Institute of Technology, Greece; **Nerukh Dmitry,** Senior Lecturer Aston University, Birmingham (United Kingdom); **Pavlenko Anatoliy,** Professor of Kielce University of Technology, Department of Building Physics and Renewable Energy Kielce (Poland); **Вовк Р. В.,** д. ф.-м. н., проф., Харківський національний університет імені В. Н. Каразіна, Харків (Україна); **Гламаздін О. В.,** к. ф.-м. н., старший науковий співробітник, Національний науковий центр «Харківський фізико-технічний інститут», Харків (Україна); **Гришанов М. І.,** д. ф.-м. н., проф., Український державний університет залізничного транспорту, Харків (Україна); **Желєзний В. П.,** д. т. н., проф., Одеська національна академія харчових технологій, Одеса (Україна); **Ільчук Г. А.,** д. ф.-м. н., проф., Національний університет «Львівська політехніка», Львів (Україна); **Мар'янчук П. Д.,** д. ф.-м. н., проф., Чернівецький національний університет ім. Ю. Федьковича, Чернівці (Україна); **Маслов В. П.,** д. т. н., проф., Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ (Україна); **Старіков В. В.,** к. ф.-м. доцент, Національний технічний університет «Харківський політехнічний інститут», Харків (Україна); **Ткаченко В. І.,** д. ф-м. н., проф., Харківський національний університет імені В. Н. Каразіна, Харків (Україна); **Ціж Б. Р.,** д. т. н., проф., Львівський національний університет ветеринарної медицини та біотехнологій імені С. З. Ґжицького, Львів (Україна)

ТЕХНОЛОГІЇ ОРГАНІЧНИХ ТА НЕОРГАНІЧНИХ РЕЧОВИН

Martins Luisa, Associate Professor of Universidade de Lisboa, Lisbon (Portugal); **Arvaidas Galdikas,** Professor Kaunas University of Technology, Department of Physics, Kaunas (Lithuania); **Carda Juan B.,** Professor of Universidad Jaume I, Department of Inorganic Chemistry, Castellon de la Plana (Spain); **Gerasimchuk Nikolay,** Professor of Missouri State University, Springfield (United States); **Rotaru Andrei,** Professor of University of Craiova (Craiova); **Sprynskyy Myroslav,** Nicolaus Copernicus University in Torun, Department of Environmental Chemistry and Bioanalytics, Torun (Poland); **Zeng Liang,** Tianjin University, Tianjin (China); **Барсуков В. З.,** д. х. н., проф., Київський національний університет технологій та дизайну, Київ (Україна); **Вахула Я. І.,** д. т. н., проф., Національний університет «Львівська політехніка», Львів (Украина); **Дорошенко А. О.,** д. х. н., проф., Харківський національний університет імені В. Н. Каразіна, Харків (Україна); **Капустін О. Є.,** д. х. н., проф., Приазовський державний технічний університет, Маріуполь (Україна); **Колосов О. Є.,** д. т. н., Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ (Україна); **Кривенко П. В.,** д. т. н., проф., Київський національний університет будівництва і архітектури, Київ (Україна); **Плаван В. П.,** д. т. н., проф., Київський національний університет технологій та дизайну, Київ (Україна); **Рошаль О. Д.,** д. х. н., Харківський національний університет імені В. Н. Каразіна, Харків (Україна); **Сухий К. М.,** д. т. н., проф., Український державний хіміко-технологічний університет, Дніпро (Україна); **Чумак В. Л.,** д. х. н., проф., Національний авіаційний університет, Київ (Україна)

ПРИКЛАДНА МЕХАНІКА

Aifantis Elias, Aristotle University of Thessaloniki, Thessaloniki (Greece); **Andrianov Igor,** Professor of RWTH Aachen University, Department of General Mechanics, Aachen (Germany); **Lewis Roland W.,** Swansea University, Swansea (United Kingdom); **Sapountzakis Evangelos,** National Technical University of Athens, Athens (Greece); **Tornabene Francesco,** University of Bologna, Bologna (Italy); **Uchino Kenji,** Pennsylvania State University, University Park (USA); **Visser, Frank C.,** Flowserve, Etten-Leur (Netherlands); **Аврамов К. В.,** д. т. н., проф., Інститут проблем машинобудування ім. А. М. Підгорного Національної академії наук України, Харків (Україна); **Астанін В. В.,** д. т. н., проф., Національний авіаційний університет, Київ (Україна); **Ахундов В. М.,** д. ф.-м. н., професор, Національна металургійна академія України, Дніпро (Україна); **Легеза В. П.,** д. т. н., проф., Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ (Україна); **Лобода В. В.,** д. ф.-м. н., професор, Дніпровський національний університет імені Олеся Гончара (Україна); **Львов Г. І.,** д. т. н., проф., Національний технічний університет «Харківський політехнічний інститут», Харків (Україна); **Пукач П. Я.,** д. т. н., проф., Національний університет «Львівська політехніка», Львів (Україна); **Ромуальдович С. І.,** д. т. н., проф., Національний авіаційний університет, Київ (Україна); **Філімоніхін Г. Б.,** д. т. н., проф., Центральноукраїнський національний технічний університет, Кропивницький (Україна); **Фомичов П. О.,** д. т. н., проф., Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків (Україна); **Ярошевич М. П.,** д. т. н., проф., Луцький національний технічний університет, Луцьк (Україна)

ЕНЕРГОЗБЕРІГАЮЧІ ТЕХНОЛОГІЇ ТА ОБЛАДНАННЯ

Acaroglu Mustafa, Selcuk Universitesi, Konya (Turkey); **Besagni Giorgio,** Ricerca sul Sistema Energetico, Milan (Italy); **Calise Francesco,** Universita degli Studi di Napoli Federico II, Naples (Italy); **Guerrero Josep M.,** Aalborg Universitet, Aalborg (Denmark); **Li Haiwen,** Kyushu University, Fukuoka (Japan); **Ma Zhenjun,** University of Wollongong, Wollongong (Australia); **Morosuk Tatiana,** Technical University of Berlin, Berlin (Germany); **Popescu Mihaela,** University of CraiovaCraiova (Romania); **Santamouris Mattheos,** University of New South Wales, Sydney (Australia); **Sutikno Tole,** Professor of Universitas Ahmad Dahlan, Department of Electrical Engineering, Yogyakarta (Indonesia); **Авраменко А. О.,** д. т. н., проф., Інститут технічної теплофізики Національної академії наук України, Київ (Україна); **Єрохов В. Ю.,** д. т. н., проф., Національний університет «Львівська політехніка», Львів (Україна); **Любарський Б. Г.,** д. т. н., проф., Національний технічний університет «Харківський політехнічний інститут», Харків (Україна); **Русанов А. В.,** д. т. н., проф., Інститут проблем машинобудування ім. А. М. Підгорного Національної академії наук України, Харків (Україна); **Терещенко Т. О.,** д. т. н., проф., Національний технічний університет України «Київський політехнічний інститут», Київ (Україна); **Фіалко Н. М.,** д. т. н., проф., Інститут технічної теплофізики Національної академії наук України, Київ (Україна)

ІНФОРМАЦІЙНО-КЕРУЮЧІ СИСТЕМИ

Sattarova Ulkar Eldar, Associate Professor Azerbaijan University of Architecture and Construction, Department of Information technologies and systems, Baku (Azerbaijan); **Starovoitov Valery,** Professor, Doctor of sciences, United Institute of Informatics Problems, National Academy of Sciences of Belarus, Minsk (Belarus); **Безрук В. М.,** д. т. н., проф., Харківський національний університет радіоелектроніки, Харків (Україна); **Величко О. М.,** д. т. н., професор, Державне підприємство «Укрметртестстандарт», Київ (Україна); **Уривський Л. О.,** д. т. н., проф., Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ (Україна); **Щербакова Г. Ю.,** д. т. н., доцент, Одеський національний політехнічний університет, Одеса (Україна); **Яцків В. В.,** д. т. н., доцент, Тернопільський національний економічний університет, Тернопіль (Україна)

ЕКОЛОГІЯ

Kisi Ozgur, Ilia State University, Tbilisi (Georgia); **Makarynskyy Oleg,** Australian Institute of Marine Science (Australia); **Scholz Miklas,** Lunds Universitet, Lund (Sweden); **Бойченко С. В.,** д. т. н., проф., Національний авіаційний університет, Київ (Україна); **Гомеля М. Д.,** д. т. н., проф., Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ (Україна); **Ремез Н. С.,** д. т. н., Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ (Україна); **Шведчикова І. О.,** д. т. н., проф., Київський національний університет технологій та дизайну, Київ (Україна)

ТЕХНОЛОГІЇ ТА ОБЛАДНАННЯ ХАРЧОВИХ ВИРОБНИЦТВ

Adegoke Gabriel, Professor of University of Ibadan, Department of Food Technology, Ibadan (Nigeria); **Barreca Davide,** Universita degli Studi di Messina, Messina (Italy); **Effat Baher,** National Research Centre, Cairo (Egypt); **Erkmen Osman,** Gaziantep Universitesi, Gaziantep (Turkey); **Hafiz Ansar Rasul Suleria,** PhD, Kansas State University, Department of Food, Nutrition, Dietetics and Health, Manhattan (USA); **Modi Vinod,** Central Food Technological Research Institute India, Fish and Poultry Technology, Mysore (India); **Бурдо О. Г.,** д. т. н., проф., Одеська національна академія харчових технологій, Одеса (Україна); **Павлюк Р. Ю.,** д. т. н., проф., Харківський державний університет харчування та торгівлі, Харків (Україна)

МАТЕРІАЛОЗНАВСТВО

Apostolopoulos Charis, Patras University, Patra (Greece); **Gubicza Jenő,** Eötvös Loránd University, Budapest (Hungary); **Gupta Manoj,** National University of Singapore, Singapore City (Singapore); **Букетов А. В.,** д. т. н., проф., Херсонська державна морська академія, Херсон, (Україна); **Геворкян Е. С.,** д. т. н., проф., Український державний університет залізничного транспорту, Харків (Україна); **Дубок В. А.,** д. х. н., проф., Київський національний університет імені Тараса Шевченка, Київ (Україна); **Дурягіна З. А.,** д. т. н., проф., Національний університет «Львівська політехніка», Львів (Україна); **Єфременко В. Г.,** д. т. н., проф., ДВНЗ «Приазовський державний технічний університет», Маріуполь (Україна); **Соболь О. В.,** д. ф.-м. н., проф., Національний технічний університет «Харківський політехнічний інститут», Харків (Україна); **Яремій І. П.,** д. ф.-м. н., проф., Прикарпатський національний університет імені Василя Стефаника, Івано-Франківськ (Україна)

EDITOR IN CHIEF

Demin Dmitriy
Professor of the National Technical University «Kharkiv Polytechnic Institute»,
Director of Private Company «Technology Center», Kharkiv (Ukraine)

Terziyan Vagan
Professor of the University of Jyvaskyla (Finland)

EDITORIAL BOARD

ENGINEERING TECHNOLOGICAL SYSTEMS

Awrejcewicz Jan, Professor of Lodz University of Technology, Department of Automation, Biomechanics and Mechatronics, Lodz (Poland); **Kindrachuk Myroslav,** Professor of National Aviation University, Department of Tribological material science, powder metallurgy, functional materials, Kyiv (Ukraine); **Korzhyk Volodymyr,** Doctor of Technical Sciences, Director of the Chinese-Ukrainian E. O. Paton Welding Institute (CUPWI), Guangzhou (China); **Marcin Kamiński,** Professor of Lodz University of Technology, Department of Structural Mechanics, Lodz (Poland); **Ulusoy Uğur,** Professor of Cumhuriyet Universitesi, Department of Mining Engineering, Sivas (Turkey); **Shen Houfa,** Professor of Tsinghua University, School of Materials Science and Engineering, Beijing (China); **Zagirnyak Mykhaylo,** Professor of Kremenchuk Mykhailo Ostrohradskiy National University, Department of electric machines and apparatus, Kremenchuk (Ukraine); **Zaloga Viliam,** Professor of Sumy State University, Department of manufacturing engineering, machines and tools, Sumy (Ukraine)

INFORMATION TECHNOLOGY. INDUSTRY CONTROL SYSTEMS

Cardoso Jorge, Professor of University of Coimbra, Faculty of Science and Technology, Coimbra (Portugal); **Iyengar Sitharama Sitharama,** Professor of Florida International University, School of Computing and Information Sciences, Miami (USA); **Jakab Frantisek,** Associate Professor of Technical University of Kosice, Department of Computers and Informatics, Kosice (Slovak Republic); **Lakhno Valeriy,** Professor of European University, Department of Managing Information Security, Kyiv (Ukraine); **Lytvyn Vasyl,** Professor of Lviv Polytechnic National University, Department of Information Systems and Networks, Lviv (Ukraine); **Omelayenko Borys,** PhD, Senior Software Engineer at Elsevier Amsterdam Area, Amsterdam (Netherlands); **Ostapov Serhii,** Professor of Yuri Fedkovych Chernivtsi National University, Department of Computer systems software, Chernivtsi (Ukraine); **Peleshchyshyn Andriy,** Professor of Lviv Polytechnic National University, Department of social communication and information activities, Lviv (Ukraine); **Terziyan Vagan,** Professor of University of Jyvaskyla, Department of Mathematical Information Technology, Jyvaskyla (Finland); **Teslyuk Vasyl,** Professor of Lviv Polytechnic National University, Department of Automated Control Systems, Lviv (Ukraine); **Wrycza Stanislaw,** Professor of Uniwersytet Gdanski, Department of Business Informatics, Gdańsk (Poland); **Zholtkevych Grygoriy,** Professor of Karazin Kharkiv National University, Department of Theoretical and Applied Computer Science of School of Mathematics and Computer Science, Kharkiv (Ukraine)

CONTROL PROCESSES

Butko Tatiana, Professor of Ukrainian State University of Railway Transport, Department of operational work and international transportation, Kharkiv (Ukraine); **Demin Dmitriy,** Professor of National Technical University «Kharkiv Polytechnic Institute», director of the Private Company «Technology Center», Kharkiv (Ukraine); **Gogunsky Viktor,** Professor of Odessa National Politechnic University, Department of Management of life safety systems, Odessa (Ukraine); **Myamlin Sergey,** Professor of Dnipropetrovsk National University of Rail Transpor, Dnipro (Ukraine); **Panchenko Sergii,** Professor of Ukrainian State University of Railway Transport, Department of Automatic and computer remote control of train traffic, Kharkiv (Ukraine); **Prokhorchenko Andrii,** Professor of Ukrainian State University of Railway Transport, Department of Operational Work Management, Kharkiv (Ukraine); **Rab Nawaz Lodhi,** PhD, COMSATS Institute of Information Technology Sahiwal Campus (Pakistan); **Sira Oksana,** Professor of National Technical University «Kharkiv Polytechnic Institute», Department of distributed information systems and cloud technologies, Kharkiv (Ukraine)

MATHEMATICS AND CYBERNETICS - APPLIED ASPECTS

Ahmad Izhar, Associate Professor of King Fahd University of Petroleum and Minerals, Department of Mathematics and Statistics, Dhahran (Saudi Arabia); **Atamanyuk Igor,** Professor Mykolaiv National Agrarian University, Department of Higher and Applied Mathematics, Mykolaiv (Ukraine); **Hari Mohan Srivastava,** Professor University of Victoria, Department of Mathematics and Statistics, Victoria (Canada); **Kanellopoulos Dimitris,** PhD, University of Patras, Department of Mathematics, Patra (Greece); **Kondratenko Yuriy,** Professor Petro Mohyla Black Sea National University, Department of Intelligent Information Systems, Mykolaiv (Ukraine); **Romanova Tetyana,** Professor Institute for Problems in Machinery of National Academy of Sciences of Ukraine, Department of Mathematical Modeling and Optimal Design, Kharkiv (Ukraine); **Savanevych Vadym,** Professor State Space Agency of Ukraine, Kyiv (Ukraine); **Trujillo Juan J.,** Professor of Universidad de la Laguna, Faculty of Mathematics, San Cristobal de La Laguna (Spain); **Weber Gerhard Wilhelm,** Professor of Middle East Technical University, Institute of Applied Mathematics, Ankara (Turkey)

APPLIED PHYSICS

Bobitski Yaroslav, Professor of University of Rzeszow, Department of mechatronics, Rzeszów (Poland); **Glamazdin Alexander,** PhD, National Science Center «Kharkov Institute of Physics and Technology», Kharkiv (Ukraine); **Grishanov Nikolay,** Professor of Ukrainian State University of Railway Transport, Department of Physics of plasmas, Controlled Nuclear Fusion, Kharkiv (Ukraine); **Ilchuk Hryhoriy,** Professor of Lviv Polytechnic National University, Department of General Physics, Lviv (Ukraine); **Machado Jose Antonio Tenreiro,** Professor of Polytechnic of Porto, Institute of Engineering, Department of Electrical Engineering, (Portugal); **Magafas Lykourgos,** Professor of Eastern Macedonia & Thrace Institute of Technology, Department of Electrical Engineering (Greece); **Maryanchuk Pavlo,** Professor of Yuriy Fedkovych Chernivtsi National University, Departmetn of Physics, (Ukraine); **Maslov Volodymyr,** Professor of National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Department of Scientific, analytic and ecological instruments and systems, Kyiv (Ukraine); **Nerukh Dmitry,** Senior Lecturer Aston University, Department of Mathematics, Birmingham, United Kingdom; **Pavlenko Anatoliy,** Professor of Kielce University of Technology, Department of Building Physics and Renewable Energy, Kielce (Poland); **Starikov Vadim,** Associate Professor of National Technical University «Kharkiv Polytechnic Institute», Department of Physics of metals and semiconductors, Kharkiv (Ukraine); **Tkachenko Viktor,** Professor of V. N. Karazin Kharkiv National University, Department of Physics of Innovative Energy & Technology & Ecology, Kharkiv (Ukraine); **Tsizh Bohdan,** Professor of Stepan Gzhytskyi National University of Veterinary Medicine and Biotechnologies Lviv, Department of General Technical Subjects and Production Quality Contro, Lviv (Ukraine); **Vovk Ruslan,** Professor of Karazin Kharkiv National University, Department of low temperature physics, Kharkiv (Ukraine); Zhelezny Vitaly, Professor of Odessa National Academy of Food Technologies, Department of Thermal Physics and Applied Ecology, Odessa (Ukraine)

TECHNOLOGY ORGANIC AND INORGANIC SUBSTANCES

Arvaidas Galdikas, Professor Kaunas University of Technology, Department of Physics, Kaunas (Lithuania); **Barsukov Viacheslav,** Professor Kyiv National University of Technologies and Design, Department for Electrochemical Power Engineering and Chemistry, Kyiv (Ukraine); **Carda Juan B.,** Professor of Universidad Jaume I, Department of Inorganic Chemistry, Castellon de la Plana (Spain); **Chumak Vitaliy,** Professor of National Aviation University, Department of Chemistry and Chemical Engineering, Kyiv (Ukraine); **Doroshenko Andrey,** V. N. Karazin Kharkiv National University, Department of organic chemistry, Kharkov (Ukraine); **Gerasimchuk Nikolay,** Professor of Missouri State University, Department of Chemistry, Springfield (United States); **Rotaru Andrei,** Professor of University of Craiova, Department of Physics (Craiova); **Kapustin Alexey,** Professor of Pryazovskyi State Technical University, Department of Chemistry, Mariupol (Ukraine); **Kolosov Akeksandr,** Professor of National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Department of Chemical, Polymeric and Silicate Machine Building, Kyiv (Ukraine); **Krivenko Pavel,** Professor Kyiv National University of Construction and Architecture, Scientific Research Institute for Binders and Materials, Kyiv (Ukraine); **Martins Luisa,** Associate Professor of Universidade de Lisboa, Instituto Superior Tecnico, Lisbon (Portugal); **Plavan Viktoriia,** Professor Kyiv National University of Technologies and Design, Department of Applied Ecology, Technology of Polymers and Chemical Fiber, Kyiv (Ukraine); **Roshal Alexander,** V. N. Karazin Kharkiv National University, Research Institute of Chemistry, Kharkiv (Ukraine); **Rotaru Andrei,** University of Craiova, Department of Physics (Craiova); **Sprynskyy Myroslav,** Nicolaus Copernicus University in Torun, Department of Environmental Chemistry and Bioanalytics, Torun (Poland); **Sukhyy Mikhaylo,** Professor of Ukrainian State University of Chemical Technology, Department of Processing of Plastics and Photo-, Nano- and polygraphic materials, Dnipro (Ukraine); **Vakhula Yaroslav,** Professor of Lviv Polytechnic National University, Department of Silicate Engineering, Lviv (Ukraine); **Zeng Liang,** Tianjin University, School of Chemical Engineering and Technology, Tianjin (China)

APPLIED MECHANICS

Aifantis Elias, Aristotle University of Thessaloniki, Thessaloniki (Greece); **Akhundov Vladimir,** Professor of National metallurgical academy of Ukraine, Department of Applied mechanics, Dnipro (Ukraine); **Andrianov Igor,** Professor of RWTH Aachen University, Department of General Mechanics, Aachen (Germany); **Astanin Vyacheslav,** Professor of National Aviation University, Department of Mechanics, Kyiv (Ukraine); **Avramov Konstantin,** Professor of A. Podgorny Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Department of reliability and dynamic strength, Kharkiv (Ukraine); **Filimonikhin Gennadiy,** Professor of Central Ukrainian National Technical University, Department of Machine Parts and Applied Mechanics, Kropyvnytskyi (Ukraine); **Fomychov Petro,** Professor of National Aerospace University «Kharkiv Aviation Institute» named after N. E. Zhukovsky, Department of Aircraft strength, Kharkiv (Ukraine); **Legeza Viktor,** Professor of National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Department of Computer Systems Software, Kyiv (Ukraine); **Lewis Roland W.,** Swansea University, Department of Civil Engineering, Swansea (United Kingdom); **Loboda Volodymyr,** Professor of Oles Honchar Dnipro National University (Ukraine); **Lvov Gennadiy,** Professor of National Technical University «Kharkiv Polytechnic Institute», Department of dynamics and strength of machines, Kharkiv (Ukraine); **Pukach Petro,** Professor of Lviv Polytechnic National University, Department of Computational Mathematics and Programming, Lviv (Ukraine); **Romualdovich Sergey,** Professor of National Aviation University, Department of Aircraft construction, Kyiv (Ukraine); **Sapountzakis Evangelos,** National Technical University of Athens, Civil Engineering, Athens (Greece); **Tornabene Francesco,** University of Bologna, Department DICAM, Bologna (Italy); **Uchino Kenji,** Pennsylvania State University, Electrical Engineering, University Park (USA); **Visser, Frank C.,** Flowserve, AMSS, Etten-Leur (Netherlands); **Yaroshevich Nikolai,** Professor of Lutsk National Technical University, Department of Branch Engineering, Lutsk (Ukraine)

ENERGY-SAVING TECHNOLOGIES AND EQUIPMENT

Acaroglu Mustafa, Selcuk Universitesi, Department Energy Division, Konya (Turkey); **Avramenko Andriy,** Professor of Institute of Engineering Thermophysics of National academy of sciences of Ukraine, Department of heat and mass transfer and hydrodynamics in heat power equipment, Kyiv (Ukraine); **Besagni Giorgio,** Ricerca sul Sistema Energetico, Energy Systems Development Department, Milan (Italy); **Calise Francesco,** Universita degli Studi di Napoli Federico II, Department of Industrial Engineering, Naples (Italy); **Fialko Nataliia,** Professor of Institute of Engineering Thermophysics of National academy of sciences of Ukraine, Department of energy efficient of heat technologies, Kyiv (Ukraine); **Guerrero Josep M.,** Aalborg Universitet, Energy Technology, Aalborg (Denmark); **Li Haiwen,** Kyushu University, Platform of Inter/Transdisciplinary Energy Research (Q-PIT), Fukuoka (Japan); **Liubarskyi Borys,** Professor of National Technical University «Kharkiv Polytechnic Institute», Department of electrical transport and diesel locomotive, Kharkiv (Ukraine); **Ma Zhenjun,** University of Wollongong, Sustainable Buildings Research Centre, Wollongong (Australia); **Morosuk Tatiana,** Technical University of Berlin, Institute for Energy Engineering, Berlin (Germany); **Popescu Mihaela,** University of Craiova, Department of Electromechanics, Environment and Applied Informatics, Craiova (Romania); **Rusanov Andrii,** Professor of A. Podgorny Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, Department of Hydroaeromechanics of Power Machines, Kharkiv (Ukraine); **Santamouris Mattheos,** University of New South Wales, Built Environment, Sydney (Australia); **Sutikno Tole,** Professor of Universitas Ahmad Dahlan, Department of Electrical Engineering, Yogyakarta (Indonesia); **Tereshchenko Tatiana,** Professor of National Technical University of Ukraine «Kyiv Polytechnic Institute», Department of Industrial Electronics, Kyiv (Ukraine); **Yerokhov Valerij,** Professor of Lviv Polytechnic National University, Department of Semiconductor Electronics, Lviv (Ukraine)

INFORMATION AND CONTROLLING SYSTEM

Bezruk Valeriy, Professor of Kharkiv National University of Radio Electronics, Department of Information and Network Engineering, Kharkiv (Ukraine); **Shcherbakova Galyna,** Associate professor of Odessa National Polytechnic University, Department of electronic apparatus & information technology, Odessa (Ukraine); **Uryvsky Leonid,** Professor of National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Department of telecommunication, Kyiv (Ukraine); **Sattarova Ulkar Eldar,** Associate Professor Azerbaijan University of Architecture and Construction, Department of Information technologies and systems, Baku (Azerbaijan); **Starovoitov Valery,** Professor, Doctor of sciences, United Institute of Informatics Problems, National Academy of Sciences of Belarus, Laboratory of System Identification, Minsk (Belarus); **Velychko Oleh,** Professor of State Enterprise «Ukrmetrteststandard», Institute of Electromagnetic Measurements, Kyiv (Ukraine); **Yatskiv Vasyl,** Associate professor of Ternopil National Economic University, Department of Cyber Security, Ternopil (Ukraine)

ECOLOGY

Boichenko Sergii, Professor of National aviation universit, Department of ecology, Kyiv (Ukraine); **Gomelia Nikolai,** Professor of National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Department of Ecology and Technology of Plant Polymers, Kyiv (Ukraine); **Kisi Ozgur,** Ilia State University, Faculty of Natural Sciences and Engineering, Tbilisi (Georgia); **Makarynskyy Oleg,** Australian Institute of Marine Science, Arafura Timor Research Facility (Australia); **Remez Natalya,** Professor of National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Department of Environmental Engineering, Kyiv (Ukraine); **Scholz Miklas,** Lunds Universitet, Department of Water Resources Engineering, Lund (Sweden); **Shvedchykova Iryna,** Professor Kyiv National University of Technologies and Design, Department of Electronics and Electrical Engineering, Kyiv (Ukraine)

TECHNOLOGY AND EQUIPMENT OF FOOD PRODUCTION

Adegoke Gabriel, Professor of University of Ibadan, Department of Food Technology, Ibadan (Nigeria); **Barreca Davide,** Universita degli Studi di Messina, Department of Chemical Biological Pharmaceutical and Environmental Sciences, Messina (Italy); **Burdo Oleg,** Professor of Odessa National Academy of Food Technologies, Department of processes, equipment and energy management, Odesa (Ukraine); **Effat Baher,** National Research Centre, Dairy Science Department, Cairo (Egypt); **Erkmen Osman,** Gaziantep Universitesi, Department of Food Engineering, Gaziantep (Turkey); **Hafiz Ansar Rasul Suleria,** PhD, Kansas State University, Department of Food, Nutrition, Dietetics and Health, Manhattan (USA); **Modi Vinod,** Central Food Technological Research Institute India, Department of Meat, Fish and Poultry Technology, Mysore (India); **Pavlyuk Raisa,** Professor of Kharkiv State University of Food Technology and Trade, Department of Technology processing of fruits, vegetables and milk, Kharkiv (Ukraine)

MATERIALS SCIENCE

Apostolopoulos Charis, Patras University, Department of Mechanical Engineering and Aeronautics, Patra (Greece); **Buketov Andriy,** Professor of Kherson State Maritime Academy, Department of Transport technologies, Kherson (Ukraine); **Dubok Vitalii,** Professor of Taras Shevchenko National University of Kyiv, Department of Radiophysical Phaculyty, semiconductor physical chair, Kyiv (Ukraine); **Duriagina Zoia,** Professor of Lviv Polytechnic National University, Department of Applied Materials Science and Materials Engineering, Lviv (Ukraine); **Efremenko Vasily,** Professor of State Higher Educational Institution «Priazoivskyi State Technical University», Department of Physics, Mariupol (Ukraine); **Gevorkyan Edvin,** Professor of Ukrainian State University of Railway Transport, Department of Quality, standartization, sertification and materials making technology, Kharkiv (Ukraine); **Gubicza Jenő,** Eötvös Loránd University, Department of Materials Physics, Budapest (Hungary); **Gupta Manoj,** National University of Singapore, Singapore City (Singapore); **Sobol Oleg,** Professor of National Technical University «Kharkiv Polytechnic Institute», Department of Materials Science, Kharkiv (Ukraine); **Yaremiy Ivan,** Professor of Vasyl Stefanyk Precarpathian National University, Department of Material Science and New Technology, Ivano-Frankivsk (Ukraine)

Establishers
PC «TECHNOLOGY CENTER»
Ukrainian State University of Railway Transport

Publisher
PC «TECHNOLOGY CENTER»

Editorial office's and publisher's address:
Shatilova dacha str., 4, Kharkiv, Ukraine, 61145

Contact information
Tel.: +38 (057) 750-89-90
E-mail: eejet.kh@gmail.com
Website: http://www.jet.com.ua, http://journals.uran.ua/eejet

Journal Indexing

- Scopus
- CrossRef
- American Chemical Society
- EBSCO
- Index Copernicus
- Российский индекс научного цитирования (РИНЦ)
- Ulrich's Periodicals Directory
- DRIVER
- Bielefeld Academic Search Engine (BASE)
- WorldCat
- Electronic Journals Library
- DOAJ
- ResearchBib
- Polska Bibliografia Naukowa
- Directory of Research Journals Indexing
- Directory Indexing of International Research Journals
- Open Academic Journals Index
- Sherpa/Romeo

Свідоцтво про державну реєстрації журналу
КВ № 21546-11446 ПР від 08.09.2015

Атестовано
Вищою Атестаційною Комісією України
Перелік № 12 постанови Президії ВАК № 1-05.36 від 11.06.03

Постановою Президії ВАК України
№ 1-05/2 від 27.05.2009, № 1-05/3 від 08.07.2009
Бюлетень ВАК України

Наказом Міністерства освіти і науки України
№ 612 від 07.05.2019
Категорія А

Підписано до друку
23.05.2019 р.

Формат 60 × 84 1/8.
Ум.-друк. арк. 7,75. Обл.-вид. арк. 7,21
Тираж 1000 екз.

Механізм ферментативної кінетики у біоклітині моделювався багатоканальною системою масового обслуговування. Процес біодеградації з субстратним інгібіюванням математично описаний методом динаміки середніх. Отримана система диференційних рівнянь зі здалегіть не визначеним порядком n, що відповідає механізмам субстратного інгібіювання різноманітної інтенсивності. Для питомої швидкості деструкції знайдено повний спектр рішень V_n системи від мінімального порядку n=2 до граничного – n→∞. Повний спектр рішень необхідний для обгрунтованого вибору єдиної узагальнюючої формули. Встановлено, що параметри форми кривої для рішення з мінімальною інтенсивністю інгібіювання V_2 суттєво вирізняються із загального ряду формул спектру.

У чисельному експерименті фізичне дослідження імітувалося описом методом найменших квадратів даних, які задаються розрахунком за формулами різноманітної структури, з урахуванням несистематичної випадкової помилки. Метод чисельного експерименту дозволив задавати варійовані параметри із заданою точністю та у широкому діапазоні, що є неможливим в умовах фізичного дослідження. Серії чисельних експериментів продемонстрували можливості формули граничного порядку V_e описувати залежності всього спектру рішень. Для критичного мінімального порядку середня відносна помилка гарантовано не перевищує п'яти відсотків. Збільшення випадкової помилки завжди призводить до статистичної рівності, у точності опису формулами мінімального V_2 та граничного порядків V_e даних, які задаються розрахунком за залежністю другого порядку.

У сукупності важливість результатів чисельного моделювання фізичного експерименту полягає у доведенні можливості використання формули граничного порядку V_e у якості єдиної при описі процесів біодеструкції з різноманітними механізмами субстратного інгібіювання. Цей висновок підтверджено адекватним описом залежністю граничного порядку експериментальних даних за п'ятьма шкідливими речовинами з різноманітним ступенем інгібіювання

Ключові слова: біодеструкція, субстратне інгібіювання, система масового обслуговування, чисельний експеримент, єдина формула

UDC 504.06+577.1
DOI: 10.15587/1729-4061.2019.166571

CONSTRUCTION OF A GENERALIZED MODEL OF THE HARMFUL SUBSTANCES BIOCHEMICAL DESTRUCTION PROCESS KINETICS UNDER CONDITIONS OF SUBSTRATE INHIBITION USING THE METHODS OF SIMULATION MODELING

G. Bakharieva
PhD, Associate Professor*
E-mail: baharevaann@gmail.com
T. Falalieieva
PhD, Associate Professor**
S. Petrov
PhD, Associate Professor**
I. Mezentseva
PhD, Associate Professor*
B. Kobylianskyi
PhD, Associate Professor
Department of Occupational Safety and Ecological Safety
Teaching and Research Professional Pedagogical Institute
of Ukrainian Engineering and Pedagogical Academy
Nosakova str., 9-a, Bakhmut, Ukraine, 84500
I. Tolkunov
PhD, Associate Professor, Head of Department****
O. Bondarenko
Lecturer****
E-mail: bond62@nuczu.edu.ua
*Department of Occupational Safety and Environmental***
Department of Organic Synthesis and Nanotechnology*
***National Technical University
«Kharkiv Polytechnic Institute»
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
****Department of Pyrotechnic and Special Training
National University of Civil Defense of Ukraine
Chernyshevska str., 94, Kharkiv, Ukraine, 61023

1. Introduction

Biochemical degradation compared to physical methods of degradation of harmful substances is an environmentally friendly and relatively inexpensive way of treatment of gaseous exhausts and those dissolved in water. For gaseous exhausts insoluble in water, such as methane, a bioreactor with a washing layer is used. A bioreactor, in which the processes

© G. Bakharieva, T. Falalieieva, S. Petrov, I. Mezentseva, B. Kobylianskyi, I. Tolkunov, O. Bondarenko, 2019

of absorption and bio-oxidation in irrigation water are combined, is used for water-soluble gaseous hydrogen sulphide, sulphur dioxide, ammonia. Biodegradation of formaldehyde is a periodic aerobic or anaerobic process in tanks with active sludge. The basis for calculation in the design and practical use of biotreatment are adequate mathematical models for processes of biochemical degradation.

The theoretical ideas about the bio-oxidation process resulted in the dependence «biodegradation rate – pollutant concentration» with empirically determined coefficients. The relationship «concentration – time» obtained directly in the physical experiment cannot be used to verify the theoretical formulas either, because of its a priori low sensitivity to estimated effects. That is why the adequacy of mathematical models is verified based on the experimental relationship «biodegradation rate – pollutant concentration», obtained by preliminary processing. Experimental studies of biodegradation of most harmful substances revealed the existence of a maximum on the curve «biodegradation rate – pollutant concentration» [1–11], which proves the existence of the substrate inhibition effect in this process. The implementation of this mechanism during bio-oxidation of gaseous non-soluble (methane), soluble (hydrogen sulfide, sulfur dioxide, ammonia) and dissolved in water substances (formaldehyde) will determine the relevance of the development of the adequate mathematical model of the process of biochemical degradation with substrate inhibition.

2. Literature review and problem statement

The models of mathematical description of biodegradation with substrate inhibition, shown in Table 1, can be classified as theoretical, modified and phenomenological.

The theoretical method of research is based on compiling and solving the systems of differential equations of enzyme kinetics. In this case, this system of equations is derived from the scheme of biochemical reaction, including the formation of enzyme–substrate complexes (ESC). The mechanism of substrate inhibition is explained by the emergence of inactive ESC with the number of attached substrate molecules $n \geq 2$. In Table 1, theoretical dependences (a, b, c – empirical coefficients) are represented by models (1)–(6). The research [1] presented a formula that takes into account the substrate inhibition effect in the elementary way. Model (1) is the simplest one because it implies the existence of one inactive ESC with two non-attached substrate molecules $n=2$. In paper [12], the applicability of the model (1) for biodegradation of phenol with determination coefficients $R^2 = 0.948 - 0.985$. was demonstrated. Applicability of the model with $n=2$ in particular cases does not exclude the formation in real processes of the arrays of inactive ESC with higher than minimal order. That is why the desire to obtain theoretical dependences related to the inhibition mechanisms at $n>2$ is understandable. In order to take into account inhibition of higher intensity, two formulas (2), (3) were proposed in study [2]. To limit the number of empirically determined coefficients, inactive ESC only with $n=3$ is laid in the model (2). However, the physical picture of the incomplete solution, at which there is no ESC with $n=2$, virtually cannot be implemented.

Model (3) is the generalization of model (2) with previously unspecified $n \geq 3$. Both models have not gained a widespread use. Paper [3] virtually represents a final attempt of theoretical research to take into account the effect of substrate inhibition by the classical method with plotting the diagrams of enzymatic reactions. Two formulas (4), (5) were proposed. Model (4) is the only complete solution for $n=3$ with four empirically determinable coefficients. The latter naturally increases the capabilities of model (4) compared with three-parameter models. Model (5) is given in the general from and is not practical in character. The properties of the series in the denominator were not studied. However, knowledge of the patterns for changing coefficients c_i opens up the opportunity to reduce formula (5) to a three-parameter formula with its generalization to an arbitrary order of ESC. Article [4] proposed a specific model, which can be also interpreted as semi-empirical. As a theoretical, a four-parameter model (6) corresponds to the mechanism of inhibition that is less intensive than in model (1). ESC of second order is active, but its activity is lower than that of ESC with $n=1 (c_2 < c_1)$. A multiplier in brackets can also be regarded as a correction function. Model (6) was used practically in comparative analysis with other formulas.

Table 1

Dependences of specific biodegradation rate V on substrate concentration ρ

Model		Source
$V = \frac{a\rho}{b+\rho+c\rho^2}$,	(1)	[1]
$V = \frac{a\rho}{b+\rho+c\rho^3}$,	(2)	[2]
$V = \frac{a\rho}{b+\rho+c\rho^n}$,	(3)	
$V = \frac{a\rho}{b+\rho+c_1\rho^2+c_2\rho^3}$,	(4)	[3]
$V = \frac{a\rho}{b+\rho+\rho\sum_1^n c_i\rho^i}$,	(5)	
$V = \frac{a\rho}{b+\rho+c_1\rho^2}(1+c_2\rho)$,	(6)	[4]
$V = \frac{a\rho}{b+\rho}\exp(-c\rho)$,	(7)	[5]
$V = \frac{a\rho}{b+\rho} - c(\rho-\rho_0)$,	(8)	[6]
$V = \frac{a\rho}{b+\rho}(1-c\rho)^n$,	(9)	[7]
$V = \frac{a\rho}{b+\rho}\left(\frac{1}{1+c\rho}\right)$,	(10)	[8]
$V = \frac{a\rho}{b(1-c\rho)^m+\rho}(1-c\rho)^n$,	(11)	[9]
$V = a[\exp(-b\rho) - \exp(-c\rho)]$,	(12)	[10]
$V = a\rho^b \exp(-c\rho)$.	(13)	[11]

The modified or hybrid method for description of biodegradation is presented in Table 1 with models (7)–(11). The essence of the approach is that the known theoretical solution for $n=1$ (fractional two-parameter dependence without maximum) is corrected by some empirical function,

which phenomenologically takes into account the inhibition effect. Almost all possible types of correction functions were used. In paper [5], the correction exponential function with a negative exponent was applied as a multiplier. The authors of article [6] take into account the inhibition effect by subtraction of linear correction function. In article [7], the phenomenological correction was proposed in the form of power function. In this case, this formula became four-parameter one. In study [8], inhibition effect is empirically taken into account by multiplying by power function. Model (10) will give results similar to those calculated according to formula (7) in the region of small ranges of concentration changes. In paper [9], in addition to the power function in the form of the common multiplier, free term b of solution with $n=1$ is additionally corrected by power function in denominator. In this case, the structure of the five-parameter formula (11) is clearly overloaded. The modification method also gives good results when using three empirical coefficients. In this class of models, model (7) is the most flexible and most often used. For example, as it follows from the diagram presented in [13], a good match of experimental values and the values calculated from this formula was achieved.

Fully empirical or phenomenological approach is presented in Table 1 by models (12), (13). The phenomenological method implies the description of two processes – the fading increase in biodegradation rate (dependence $n=1$) and the actual inhibition effect – by empirical functions at the macro-level. In research [10], these two processes are represented in the form of the difference between exponential functions with negative exponents. Formula (12) is flexible enough and also successfully applied in the form of two-parametric ($b=0$) model. In study [14], determination coefficient $R^2=0.963$ in relation to phenol fermentation was achieved. In research [11], the fading increase in biodegradation rate is represented by power dependence on substrate concentration, while inhibition effect is taken into account by multiplying by exponential dependence like in model (7). Using model (13), the processes of bio-oxidation of five gaseous and water-dissolved harmful substances were successfully described [11]. It is possible to regard the impossibility of closed integration for obtaining the dependence «concentration-time» in the stationary process as the drawback of formula (13), compared to most other models. The kind of empirical dependence with maximum and inflection point characteristic of specific biodegradation rate with substrate inhibition, proposed by reference books, is limited to models (12), (13).

The search for adequate dependences of biodegradation kinetics naturally includes not only the development of new mathematical models, but also comparative analysis of the effectiveness of existing formulas. The task of the critical analysis in this case is clearly solved by comparing the known parameters of assessing the accuracy of description of experimental data. It turned out that a characteristic feature of such research is approximation of results with high determination coefficients, obtained when using different models. This conclusion was made by the authors of [15] when comparing three-parameter models (1), (7), (9), (10). In this case, model (9) was calculated for $n=0.5$; 1. In study [16], the capabilities of models (1), (4), (6), (7), (9), (11), (12) were assessed. The best results were achieved for formulas (1), (6), (7), (9), where determination coefficient fluctuated in the narrow range $R^2=0.909–0.933$. For models (4), (11), (12), $R^2=0.730–0.836$. Research [17] gave assessment of accuracy of description of experimental data by models (1), (4), (6)–(9), ((11), (12) at $b=0$). Models (1), (4) had the best result with $R^2=0.97$; 0.98, respectively. High values of determination coefficients $R^2=0.89–0.90$ are also characteristic of other formulas. In publication [18], based on the description of three series of experiments, the practical identity of the theoretical model (1) $R^2=0.924–0.976$ and purely empirical formula (12) $R^2=0.935–0.976$ were revealed. The indicators of the two-parametric model (12) at $b=0$ – $R^2=0.858–0.970$ differ insignificantly. The results, presented in [19], testify to practical match of root mean square deviations of models (1), (2), (7), (12). For models (4), (6), this indicator is lower by 10 %. In paper [20], theoretical (1) and modified (9) formulas were applied as equal with determination coefficient $R^2=0.95$. In research [21], high accuracy in the description of biodegradation kinetics by four different models was achieved: (1) – $R^2=0.9249$, (4) – $R^2=0.9237$, (7) – $R^2=0.9028$, (12) – $R^2=0.9527$. The authors of [22] showed the adequacy of models (1), (4), (6), (9) with determination coefficients within $R^2=0.947–0.995$. The data published in [23] demonstrate very close values of root mean square deviation when using models (1), (4), (7), (9), (2). In paper [24], during comparative evaluation of models (1), (4), (11) determination coefficients ranged within $R^2=0.9616–0.9877$. The data of research [25] for two series of experiments on ammonium bio-oxidation show the adequacy of the groups of models (1), (4), (6), (9), (12), and (12) (at $b=0$) – $R^2=0.91–0.99$. Extensive testing of formulas was performed by authors of [26]. In models (1), (3), (6), (7), (12), determination coefficient reached high values $R^2>0.963$. The results, obtained in [27], demonstrate practical equality of models (1), (4) – $R^2=0.989$; 0.984, respectively. Excellent conformity with the experiment was revealed in research [28] for all the studied models – (1), (4), (7), (9), (11), (12) – at $b=0$. Multi-variant description of the same experimental data at high determination coefficients testify to the possibility of using the unified generalized solution. Obviously, the quality of generalization for the given kind of a curve with zero point, maximum and inflection point will be determined not only by the magnitude of argument change range, but also by the value of random error of the experiment.

In general, critical analysis of the structures of formulas [1–11] revealed the lack of theoretical dependence for mechanisms of substrate inhibition of high intensity. In addition, a comparison of the accuracy of description of the experimental data [12–28] by various formulas showed their closeness in actual ranges of substrate concentrations. That is why the unresolved problem is finding and substantiation of the unified theoretical dependence, describing different mechanisms of substrate inhibition in the generalized form.

The only region of theoretical solutions requiring further studying is analysis of high-order formulas included in the model of the general form (5). To select the generalizing formula, it is necessary to obtain and analyze the ratio of all possible theoretical solutions. However, when using the classical approach, it is impossible to construct a common scheme for the reaction of undefined order of ESC. To solve the correspondent system of differential equations, it is necessary to accept in advance the maximal number of attached substrate molecules. This difficulty is overcome by the representation of a bio cell with enzymes in the form of a multi-channel queuing system where an enzyme is the channel. The method of dynamics of averages can be a particular implementation of this approach. Statement of the scheme of enzymatic kinetics reaction in terms of probabilistic model of the queuing theory

make it possible to get a whole range of solutions up to the limiting order of ESC $n \to \infty$. Identification of the generalizing model in the spectrum of solutions will require an extensive numerical experiment, including comparison of effectiveness of application of various formulas with consideration of random error in a physical experiment. Construction of probabilistic models of the development of processes in time and the computation experiment are the methods of simulation.

3. The aim and objectives of the study

The aim of this study is to search for and to substantiate, using the methods of simulation, a unified calculation dependence «biodegradation rate – concentration of atmosphere pollutant», generally describing the mechanisms of substrate inhibition of various intensity determined by order of inactive ESC from two ad infinitum. Pollutants include gaseous (methane, formaldehyde, hydrogen sulfide, sulfur dioxide and ammonia) non-soluble (methane), soluble (sulfur dioxide, hydrogen sulfide and ammonia) and dissolved in water (formaldehyde) harmful substances.

To accomplish the set aim, it is necessary to solve the following tasks:

– to determine the full range of theoretical formulas for calculating specific biodegradation rate, corresponding the various mechanisms of enzyme kinetics with substrate inhibition, using the method of dynamics of averages. A full range is necessary to identify the patterns of the ratio of forms of curves of calculation dependences as intensity of substrate inhibition increases and structures of formulas change;

– using the method of numerical experiment, to prove the existence in the spectrum of theoretical solutions of the unified generalizing formula, which makes it possible to perform practical calculations of bio-oxidation kinetics with substrate inhibition of any intensity in the actual range of pollutant concentrations with admissible error. The proof should include the evaluation of the influence of random error of the experiment on the conformity of the unified generalizing formula with other dependences of the spectrum.

4. Research procedure

To obtain a full range of theoretical formulas for calculating specific biodegradation rate, the probabilistic model was applied. The proposed probabilistic simulation model is based on the representation of a bio cell with enzymes in the form of a multi-channel system of queuing. The events of a substrate molecule meeting an enzyme, as well as the break of their contact, are accepted as random. Formation and decomposition of ESC are considered as the Markovian process. Biodegradation occurs as a result of a basic enzymatic act only at one attached molecule of the substrate. ESC of higher order are inactive.

Mathematical description of the model was performed using the method of dynamics of averages, in which mean numbers of ESC of different orders are determined, rather than probabilities of the state of each enzyme or substrate molecules in a bio cell. The applied method of dynamics of averages is an effective and widely used method of mathematical modeling of behavior of complex technical and military systems in the study of operations. The admission of the method is the replacement of mathematical expectation of a function with the same function of mathematical expectation. With respect to modeling the kinetics of enzymatic reactions, errors can occur only at the substrate concentration in the vicinity of a bio cell, measured by several molecules. Apparently, this admission corresponds to accepting direct proportionality between the reaction rate and the substrate concentration while compiling the classical schemes of enzymatic reactions. The formula obtained by both methods for orders of one and two are the same. Thus, the method adequately models the kinetics of the process, excluding the non-working region of virtually zero concentrations of removed harmful substances, where due to this, relative error increases dramatically even at an insignificant absolute error.

The substantiation of using the unified generalized formula was proved based on comparative assessment of accuracy of description of the specified estimated values of one function – by the dependence with another mechanism for substrate inhibition.

For comparative evaluation of the effectiveness of theoretical solutions when describing the data, corresponding to different intensity of substrate inhibition, we used the method of numerical experiment. The known merits of the method include the possibility to perform calculations in a wide range of exactly assigned varied parameters, which is virtually not realizable in a physical experiment.

At the first stage, twenty calculation points of the described functions simulated an exact physical experiment without a random error. The coefficients of the describing formula were determined by the least-squares method. The designed programs implement the widely used method of gradient or quickest descent, written down in VBA. Calculation was performed until reaching the relative change in the sum of squares of differences in one iteration step less than 10^{-16}. Relative changes of coefficients *a, b, c* in this case made up 10^{-8}–10^{-10}.

At the second stage of the study, the third series of numerical experiments using the random number generator was performed in order to assess the influence of a random error. The unit, in which experimental data were represented taking into account the existing error in a physical experiment, was added to the developed programs. The numerical experiment made it possible to vary an error with a view to assessing its influence, which is not possible when doing experiment.

5. Mathematical modeling of enzymatic kinetics with different mechanisms of substrate inhibition

The graph of the states of the elements of the proposed model was represented in Fig. 1, where: F_i is the mean quantities of ESC with attached *i*-th molecules of the substrate; λ_i and ν_i are the intensities of formation and decomposition of ESC of *i*-th order; ν_p is the intensities of product formation; S and P are mean quantities of molecules of substrate in the neighborhood of a bio cell.

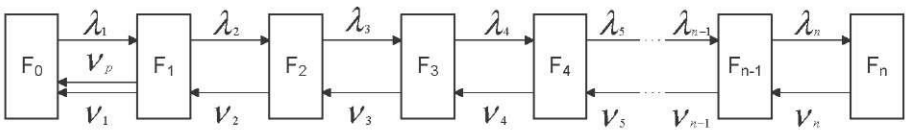


Fig. 1. Graph of possible states of enzyme in a bio cell

The method of dynamics of averages [29] enables writing down the following differential equations for the graph in Fig. 1:

$$\frac{dS}{dt}=-\lambda_1 F_0+\nu_1 F_1, \tag{14}$$

$$\frac{dF_0}{dt}=-\lambda_1 F_0+\nu_1 F_1+\nu_p F_1, \tag{15}$$

$$\frac{dF_1}{dt}=-\lambda_2 F_1+\nu_2 F_2+\lambda_1 F_0-\nu_1 F_1-\nu_p F_1, \tag{16}$$

$$\frac{dF_2}{dt}=-\lambda_3 F_2+\nu_3 F_3+\lambda_2 F_1-\nu_2 F_2, \tag{17}$$

$$\frac{dF_3}{dt}=-\lambda_4 F_3+\nu_4 F_4+\lambda_3 F_2-\nu_3 F_3, \tag{18}$$

$$\frac{dF_4}{dt}=-\lambda_5 F_4+\nu_5 F_5+\lambda_4 F_3-\nu_4 F_4, \tag{19}$$

.....

$$\frac{dF_{n-1}}{dt}=-\lambda_n F_{n-1}+\nu_n F_n+\lambda_{n-1} F_{n-2}-\nu_{n-1} F_{n-1}, \tag{20}$$

$$\frac{dF_n}{dt}=-\lambda_n F_{n-1}+\nu_n F_n, \tag{21}$$

$$\frac{dP}{dt}=\nu_p F_1. \tag{22}$$

The existence of stationary phase in the elementary enzymatic act, experimentally proved in enzymology [30], makes it possible to equal to zero the left side of the equations of the system (15)–(21). In terms of the Tikhonov theorem, equation (14) or a slow process is called a degenerate system and equations (15)–(21), or a quick process are called an attached system. It was mathematically proven [31] that the solution of the full system (14)–(21) tends to solve a degenerate system with left parts of the attached system tending to zero in the absence of the self-oscillatory processes. The Tikhonov theorem is virtually successfully used in modern theoretical studies of enzymatic reactions [32]. In a well-grounded way, we accept:

$$\frac{dF_i}{dt}=0, \tag{23}$$

and obtain the system of ordinary equations:

$$-\lambda_1 F_0+(\nu_1+\nu_P)F_1=0, \tag{24}$$

$$-\lambda_2 F_1+\nu_2 F_2=0, \tag{25}$$

$$-\lambda_3 F_2+\nu_3 F_3=0, \tag{26}$$

$$-\lambda_4 F_3+\nu_4 F_4=0, \tag{27}$$

$$-\lambda_5 F_4+\nu_5 F_5=0, \tag{28}$$

.....

$$-\lambda_n F_{n-1}+\nu_n F_n=0, \tag{29}$$

$$\lambda_n F_{n-1}-\nu_n F_n=0. \tag{30}$$

The solution to system (24)–(30) in relations to productive ESC will be:

$$F_1=\frac{\lambda_1 F}{\nu_1+\nu_p+\lambda_1\left(1+\frac{\lambda_2}{\nu_2}+\frac{\lambda_2\lambda_3}{\nu_2\nu_3}+\frac{\lambda_2\lambda_3\lambda_4}{\nu_2\nu_3\nu_4}+\ldots\frac{\lambda_2\lambda_3\lambda_4\cdots\lambda_n}{\nu_2\nu_3\nu_4\cdots\nu_n}\right)}, \tag{31}$$

where F is the total quantity of enzymes in a bio cell:

$$\lambda_i=\lambda S. \tag{32}$$

Similarly, we accept intensity of ESC decomposition as proportional to the number of unproductive attachments:

$$\nu_i=(i-1)\nu. \tag{33}$$

Condition (23) allows writing down:

$$\frac{dS}{dt}=-\frac{dP}{dt}. \tag{34}$$

With this in mind, we obtain an expression for the rate of change in the number of substrate molecules:

$$\frac{dS}{dt}=\frac{\nu_p\lambda FS}{\nu_1+\nu_p+\lambda S\left[1+\frac{\lambda S}{\nu}+\frac{1}{2}\left(\frac{\lambda S}{\nu}\right)^2+\frac{1}{6}\left(\frac{\lambda S}{\nu}\right)^3+\frac{1}{24}\left(\frac{\lambda S}{\nu}\right)^4+\ldots\frac{1}{(n-1)!}\left(\frac{\lambda S}{\nu}\right)^{n-1}\right]}. \tag{35}$$

Dependence (35) with accuracy to designations corresponds to the results obtained by the classical method for compiling the scheme of enzymatic reaction for first-order ESC (Monod formula) and second-order ESC (Andrews formula).

For the rate of concentration change specific per biomass unit, expression (35) can be represented as:

$$V=\frac{a\rho}{b+\rho\left[1+c\rho+\frac{1}{2}(c\rho)^2+\frac{1}{6}(c\rho)^3+\frac{1}{24}(c\rho)^4+\ldots\frac{1}{(n-1)!}(c\rho)^{n-1}\right]}, \tag{36}$$

where ρ is the substrate concentration; a, b, c are the experimentally determined coefficients.

Formula (36) includes the range of solutions, the size of which depends on the order n of the original system (15)–(21). System order corresponds to the order of ESC, that is, the maximal number of attached substrate molecules. In general, the whole range of solutions is represented as a set of formulas:

$$n=2,\ V_2=\frac{a\rho}{b+\rho[1+c\rho]}, \tag{37}$$

$$n=3,\ V_3=\frac{a\rho}{b+\rho\left[1+c\rho+\frac{1}{2}(c\rho)^2\right]}, \tag{38}$$

$$n=4,\ V_4=\frac{a\rho}{b+\rho\left[1+c\rho+\frac{1}{2}(c\rho)^2+\frac{1}{6}(c\rho)^3\right]}, \tag{39}$$

.....

$$n\to\infty,\ V_e=\frac{a\rho}{b+\rho\exp(c\rho)}. \tag{40}$$

An increase in the order of the system corresponds to the mechanism of substrate inhibition with greater intensity. The formulas obtained, regardless of order n include three experimentally determined parameters.

Analysis of the spectrum of solutions requires quantitative estimation of the relationship between the shapes of the curves of expressions, belonging to it. To do this, it is convenient to represent formulas (37)–(40) in the dimensionless form:

$$V^* = \frac{V}{a}, \tag{41}$$

$$V_2^* = \frac{c\rho}{cb + c\rho[1 + c\rho]}, \tag{42}$$

$$V_3^* = \frac{c\rho}{cb + c\rho\left[1 + c\rho + \frac{1}{2}(c\rho)^2\right]}, \tag{43}$$

$$V_4^* = \frac{c\rho}{cb + c\rho\left[1 + c\rho + \frac{1}{2}(c\rho)^2 + \frac{1}{6}(c\rho)^3\right]}, \tag{44}$$

$$V_e^* = \frac{c\rho}{cb + c\rho\exp(c\rho)}, \tag{45}$$

where V^* is the specific bio-oxidation rate, referred to its maximum possible value without the inhibition effect; cb is the factor of the shape of the curve, corresponding to a definite formula of the spectrum; $c\rho$ is the factor of the range of argument, determining the curve length by X-axis.

A dimensionless curve shape factor (SF) cb unambiguously determines the coordinates of maximum and inflection points for dependences of spectrum with $n \geq 2$. At small values of dimensionless argument range factor (RF) $c\rho$, formulas (42)–(45) will give close results by virtue of quick convergence of a series in denominator.

By calculation with the use of the least square method, we found coefficients in statistically significant dependences (46)–(53) of coordinates the maximum on SF cb. The coordinates, which are the original data for obtaining dependences (46)–(53), were found by the known method of numerical differentiation of calculation curves of the corresponding order. The adequacy of the method is proved by the obtained values of coefficients in expressions (46) and (50), which should be exactly equal to 1; 0.5 and 2; 0.5, respectively:

$$c\rho_{m2} = 1.0032 * (cb)^{0.5001}, \quad R^2 = 1, \tag{46}$$

$$c\rho_{m3} = 0.7017 * (cb)^{0.4233}, \quad R^2 = 0.9981, \tag{47}$$

$$c\rho_{m4} = 0.6356 * (cb)^{0.3984}, \quad R^2 = 0.9953, \tag{48}$$

$$c\rho_{me} = 0.6034 * (cb)^{0.3839}, \quad R^2 = 0.9919, \tag{49}$$

$$V_{m2}^* = \frac{1}{1 + 1.9995 * (cb)^{0.4999}}, \quad R^2 = 1, \tag{50}$$

$$V_{m3}^* = \frac{1}{1 + 2.5419 * (cb)^{0.5539}}, \quad R^2 = 0.9992, \tag{51}$$

$$V_{m4}^* = \frac{1}{1 + 2.7018 * (cb)^{0.5704}}, \quad R^2 = 0.9984, \tag{52}$$

$$V_{me}^* = \frac{1}{1 + 2.7769 * (cb)^{0.5785}}, \quad R^2 = 0.9977, \tag{53}$$

where $c\rho_{mi}$ is the dimensionless coordinate of maximum on X-axis for the curve of the i-th order; V_{mi}^* is the dimensionless coordinate of maximum on Y-axis for the curve of the i-th order; R^2 is the determination coefficient.

Comparison of coefficients in dependences (46)–(53) shows a significant quantitative difference of second-order formulas (46) and (50) from other formulas of the range. In this case, we should note proximity of dependences (48) and (49), as well as (52) and (53). These dependences are also characteristic of the coordinates of inflection points. The above analysis demonstrates the special place of curve shape for $n=2$ in the general series of the curves of higher orders. With an increase in order $n \geq 3$, the difference in curve shape is quickly leveled. Beginning with $n=4$, the curve shape parameters quantitatively differ little from shape parameters for $n \to \infty$ ($c\rho_{me}, V_{me}^*$).

Thus, formula (45), the corresponding to the mechanism of limiting order ($n \to \infty$) with the highest inhibition intensity, is close by the parameters of the curve shape to all dependences of the spectrum, except for expression (42). That is why substantiation for the use of formula (45) as generalizing should be assessment of the possibility of describing with its use the dependences with lower order and, above all, with minimal $n=2$. For complete assessment, it is also necessary to verify the quality of description of dependences, corresponding to mechanisms of higher inhibition intensity by formula (42).

6. The rationale for applicability of the unified computational formula for different models of substrate inhibition

At the first stage, two series of computational experiments were performed: description of model (43) by formula (42), as well as description of models (42)–(44) by dependence (45). Varying values of SF were accepted as overlapping the actual range: cb=0.005; 0.01; 0.025; 0.1; 0.5; 2; 10; 25; 50. Approximation accuracy was assigned by average relative error (determined by absolute magnitude) from virtually full match to admissible deviation: δ_0=005; 0.02; 0.05; 0.1. Determination coefficient R^2 and root mean square error σ_0^*, referred to limiting value of destruction rate $V=a$ were determined.

These calculations make it possible to compare beforehand the capabilities of models (42) and (45) by the description of the intermediate variant with $n=3$. In this case, the application of the least-squares method will lead to distortion of original coefficients:

$$V_{23}^* = \frac{k_a(c\rho)}{k_b(cb) + c\rho\left[1 + k_c(c\rho)\right]}, \tag{54}$$

$$V_{e3}^* = \frac{k_a(c\rho)}{k_b(cb) + c\rho\exp\left[k_c(c\rho)\right]}, \tag{55}$$

where V_{23}^* – dependence (42) describes (43); V_{e3}^* – dependence (45) describes (43); k_a, k_b, k_c are the distortion coefficients a, b, c, respectively.

For fixed values of δ_0, maximal reachable values of SF $c\rho_g$ were calculated. Obviously, higher values of $c\rho_g$ ceteris paribus must correspond to the best description of the function. Table 2 shows calculation values of $c\rho_g$ for models (42) and (45) during description of intermediate ratio (43).

Table 2

Change in maximum achievable range of argument $c\rho_g$ depending on shape factor cb at assigned relative error δ_0=0.005; 0.02; 0,05; 0.1

cb	V_e describes V_3				V_2 describes V_3			
	$c\rho_{g05}$	$c\rho_{g2}$	$c\rho_{g5}$	$c\rho_{g10}$	$c\rho_{g05}$	$c\rho_{g2}$	$c\rho_{g5}$	$c\rho_{g10}$
0.005	0.9001	1.648	2.557	3.625	0.5076	1.0645	1.8304	2.82
0.01	0.9235	1.686	2.614	3.705	0.5403	1.1124	1.8963	2.908
0.025	0.9722	1.764	2.727	3.865	0.6039	1.2061	2.0277	3.084
0.1	1.1028	1.986	3.049	4.31	0.6909	1.45	2.3787	3.564
0.5	1.309	2.504	3.842	5.39	0.8839	1.885	3.0855	4.353
2	1.653	3.223	5.151	7.207	1.1971	2.409	3.4107	4.688
10	2.3872	4.718	7.702	11.015	1.8329	2.82	4.2025	6.118
25	3.081	6.005	9.99	14.277	2.1879	3.333	5.0565	7.545
50	3.772	7.331	12.251	17.567	2.492	3.923	6.013	9.042

It follows from the data in Table 2 that formula (45) has significantly more commonality when describing the dependence with order n=3 in all the range of variations in cb at any specified accuracy δ_0. Naturally, formula (45) will also have an advantage over model (42) when describing dependences with higher order n>3. It is also necessary to note one negative property of model (42): at cb>0.5, there occurs a catastrophic (up to hundreds of thousands) increase in distortion coefficients and a sharp increase in the number of iterations. These effects arise because of poor expression of a minimum and fractionality of function (42).

Table 3 shows the results of assessment of accuracy of descriptions of function V_2 with the least order by the dependence with limiting order V_e. At fixed values of δ_0, we calculated the maximal achievable values of SF, assigned to the coordinate of a maximum on the X-axis $c\rho_g/c\rho_m$. These relative values of the range factor (RVRF) make it possible to assess visually the capabilities of model (45) in practice. The magnitude of RVRF in laboratory experiments does not usually exceed 5–6 units, except for the cases for cb<0.01 when $c\rho_g/c\rho_m$=8–10.

Table 3

Change of relative range of argument $c\rho_g/c\rho_m$ and root mean square error σ_0^*, depending on shape factor cb at relative error δ_0=0.005; 0.02; 0.05; 0.1

cb	$c\rho_g/c\rho_m$				σ_0^*			
	0.005	0.02	0.05	0.1	0.005	0.02	0.05	0.1
0.005	8.01	18.29	34.82	60.00	0.00433	0.01421	0.02759	0.04109
0.01	6.12	13.75	26.01	44.76	0.00415	0.01367	0.02654	0.03953
0.025	4.38	9.64	18.04	30.97	0.00383	0.0127	0.02465	0.03671
0.1	2.69	6.17	11.37	19.30	0.00301	0.01057	0.02055	0.03048
0.5	1.65	4.25	7.65	12.91	0.00162	0.00731	0.01426	0.02123
2	1.22	3.21	6.11	10.27	0.00081	0.00439	0.0091	0.01361
10	0.97	2.62	5.24	8.76	0.00034	0.00217	0.0048	0.00719
25	0.89	2.42	5.00	8.35	0.0002	0.00139	0.0032	0.00481
50	0.86	2.32	4.89	8.16	0.00014	0.00098	0.00232	0.0035

It follows from the data in Table 3, that at high accuracy δ_0=0.005, practical capabilities of model (45) are limited to small values of SF cb=0.01. However, at a 5 % relative error, formula (45) already describes with guarantee an actual range of changes in SF, which for the dependence with minimal order is focused in the region of cb<0.5. For models with a higher order, the capabilities of formula (45) are higher by virtue of proximity of curves' shapes.

The values of relative root mean square error σ_0^* decrease to very small values at an increase in cb, which indicates lesser visibility of the application of this indicator compared to an average relative error. Determination coefficient also is inferior to indicator δ_0 in sensitivity in relation to varying parameters.

The above analysis was performed in the coordinates of dimensionless parameters $c\rho_{gn}$ and cb_n for the described dependences V_n^* of the n-th order. In the framework of the computation experiment, we calculated range factor $c\rho_{gen}$ and shape factor cb_{en}, corresponding to formula V_{en}^*, that describe dependence V_n^*. Fig. 2 shows the results of the second series of the computational experiment in calculated coordinates of the describing formula V_{en}^*.

For each group of curves, the assigned relative error varies from top to bottom: δ_0=0.1; 0.05; 0.02; 0.005.

It follows from the data in Fig. 2 that the admissible range of existing calculated parameters $c\rho_{gen}$ and cb_{en} of describing dependence V_{en}^* corresponds to each described function V_n^* of the definite order. The regions are inter-crossing and are limited at the top and at the bottom by curves with maximum δ_0=0.1 and minimum δ_0=0.005 by average relative errors, respectively. On the left, the regions are limited by the Y-axis, and on the right – by extreme points of curves with different values of δ_0. At an increase in order n, the corresponding region of existence of solutions for the describing dependence expands on both axes and is shifted up Y-axis. This pattern is indicative of a natural increase in capabilities of formula V_{en}^* at an increase in the order of a described curve at a fixed relative error. The region under the lowest curve (V_2^*; δ_0=0.005) in Fig. 2 is the region of practically invariant solutions in relations to the order of describing dependence. In the insensitivity zone, the value of the range factor is so small that experimental points do not contain any significant information about the curve shape.

At the second stage of the study, to assess the influence of a random error, we performed the third series of computational experiments using the random number generator. The developed programs were supplemented with the unit, in which the experimental data V_{2s}^* were represented in the form:

$$V_{2s}^* = V_2^* + \Delta V_s^*, \tag{56}$$

where ΔV_s^* in the non-systematic random error.

The computational series included six implementations on each of the four assigned values of maximal possible random error $\Delta V_{gs}^* \geq \Delta V_s^*$. The calculated value of relative root mean square error σ_s^* corresponded to each implementation. The computational series were performed for varying parameters: at δ_0=0.05 – cb=0.05; 0.1; 10 and at cb=0.1 – δ_0=0.02; 0.05; 0.1. Magnitudes of $c\rho_g$ were accepted as equal to those calculated before for corresponding δ_0 and cb. A certain initial root-mean square deviation σ_0^* also corresponded to value δ_0. We assessed the influence of a random error on accuracy of description by formula (45) of dependence (42) – V_{e2s}^* and by formula (42) of itself – V_{22s}^*.

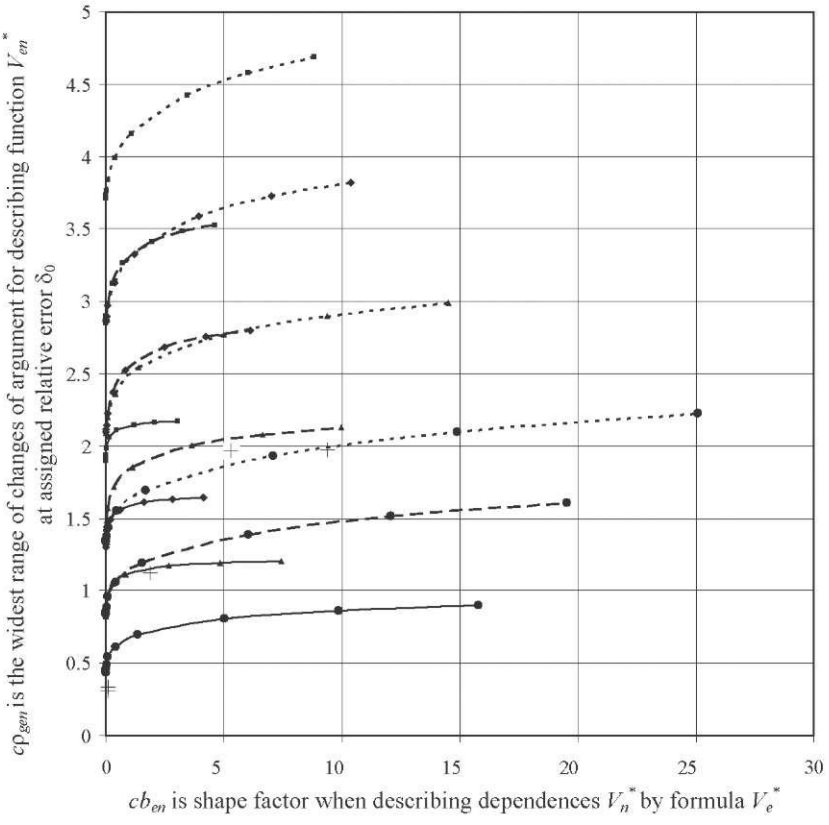


Fig. 2. Dependence of the widest range of argument change $c\rho_{gen}$ on shape factor cb_{en} when describing ratio V_n^* by formula V_e^*. Group of continuous curves – n=2; dashed curves – n=3; dotted curves – n=4

The results of assessment for the data averaged by six implementations are shown in Fig. 3, 4. It follows from the data in Fig. 3, 4 that at an increase in random error, statistical difference between descriptions V_{e2s}^* and V_{22s}^* continuously decreases. The corresponding average relative errors δ_e and δ_2 become equal when condition $\sigma_s^*/\sigma_2^* \geq 2.4$ is met. A random non-systematic error δ_s seems to absorb initial error δ_0 of mismatch of a describing and described functions.

Continuous lines – δ_e for model V_{e2s}^*, dashed lines – δ_2 for model V_{22s}^*. For each pair of curves, the assigned shape factor varies from top to bottom: cb=10; 0.1; 0.005.

Continuous lines – δ_e for model V_{e2s}^*, dashed lines – δ_2 for model V_{22s}^*. For each pair of curves, initial relative error varies from top to bottom: δ_0=0.1; 0.05; 0.02.

It is obvious that a random error leads to a distortion of numerical values of coefficients when describing a second-order function itself V_{22s}^*. A relative error in determining coefficients, averaged by six implementations, is limited by $\delta_k \leq 0.05$ only within $\delta_s \leq 0.01$ of a relative random error for the describing formula as a whole. At δ_s=0.05–0.1, an averaged error in evaluation of coefficients reaches the values of δ_k=0.2–0.35. In particular implementations, considerably larger gaps in the assessment of the accuracy of a model as a whole and accuracy of determining its coefficients were detected. To determine reliably the true values of empirical coefficients, it is necessary to perform at least six series of a very accurate physical experiment.

It is possible to argue that obtained formula V_{e2s}^* describes not original dependence V_2^*, but rather a new ratio V_{22s}^* with distorted coefficients and the error of initial mismatch δ_0 decreasing even to zero. The latter circumstance follows from the evident equality:

$$\delta_e = \delta_0 + \delta_s. \quad (57)$$

That is why when using the graphs from Fig. 2 to assess the order of experimental dependences, we should correlate the points in coordinates «$c\rho_e$–cb_e» with the curves corresponding to smaller δ_0 and larger values of n.

The points presented in Fig. 2 according to Table 4 indicate that destruction of hydrogen sulfide, sulfur dioxide and methane occurs in a zone of insensitivity to the order of a described function. For ammonia and formaldehyde (anaerobic process), the order is $n \geq 4$, for formaldehyde (aerobic process), destruction of hydrogen sulfide, sulfur dioxide, and methane occurs in a zone of insensitivity to the order of a described functions. For ammonia and formaldehyde (anaerobic process), the order is $n \geq 4$, for formaldehyde (aerobic process), $n \geq 3$.

These conclusions are supported by direct comparative estimate of capabilities of formulas of the range, shown in Table 5.

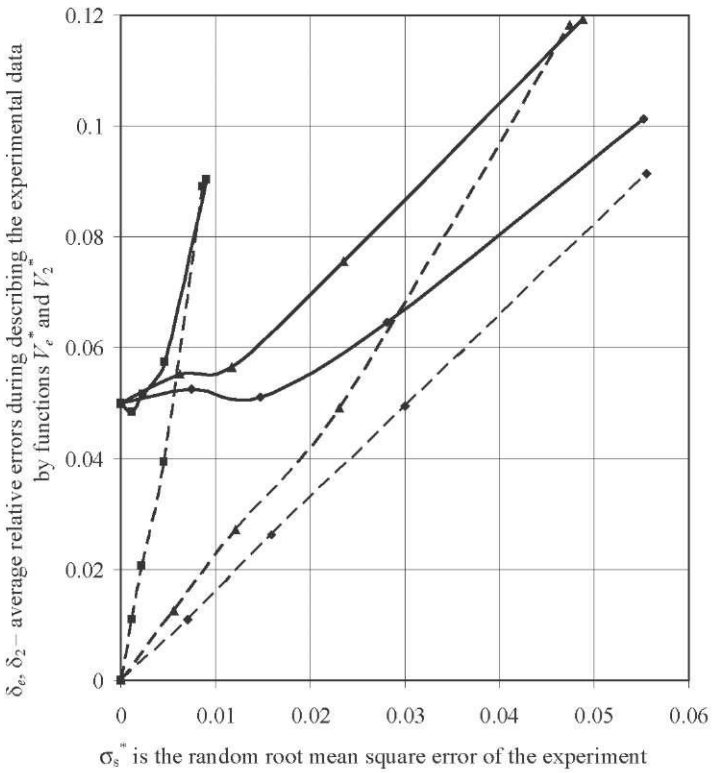


Fig. 3. Dependence of average relative errors δ_e and δ_2 on random root mean square error of experiment σ_s^* and shape factor cb at δ_0=0.05

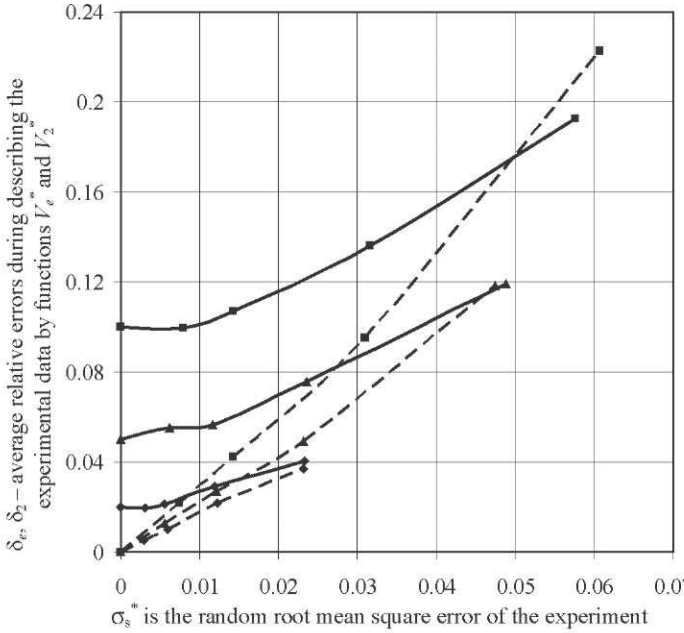


Fig. 4. Dependence of average relative errors δ_e and δ_2 on root mean square error of experiment σ_s^* and initial relative error δ_0 at cb=0.1

Table 4

Dimensionless parameters of description of experimental data [11] by formula V_e

Coordinates	Hydrogen sulfide	Sulfur dioxide	Methane	Ammonia	Formaldehyde (aerobic process)	Formaldehyde (anaerobic process)
cb_e	0.1296	0.06458	0.06493	5.276	1.873	9.373
$c\rho_e$	0.3362	0.3318	0.3121	1.966	1.124	1.972

Note: the coordinates are shown in Fig. 2 by crosses

Table 5

Comparative estimation of accuracy of description of experimental data [11] by formulas V_2, V_3, V_4 and V_e

Parameter		Hydrogen sulfide	Sulfur dioxide	Methane	Ammonia	Formaldehyde (aerobic process)	Formaldehyde (anaerobic process)
a	V_2	72.539	67.348	416.19	$1.0363 \cdot 10^5$	219.63	3,368.2
	V_3	71.509	64.465	402.42	262.20	207.08	3,314.9
	V_4	71.350	64.116	400.93	58.392	204.97	3,286.2
	V_e	71.406	64.003	400.66	39.683	203.84	3,263.0
b	V_2	39.052	25.784	2.4102	$1.1633 \cdot 10^5$	1,496.0	4,803.5
	V_3	38.534	24.172	2.2992	336.28	1,489.3	5,138.8
	V_4	38.437	23.972	2.2868	71.480	1,499.4	5,219.4
	V_e	38.488	23.898	2.2843	47.048	1,499.6	5,229.0
c	V_2	0.0041828	0.0037558	0.037996	988.73	0.0026275	0.0061665
	V_3	0.0034280	0.0028010	0.029208	0.48316	0.0014410	0.0024675
	V_4	0.0033628	0.0027198	0.028514	0.15185	0.0012904	0.0019772
	V_e	0.0033662	0.0027023	0.028427	0.11213	0.0012491	0.0017924
σ	V_2	1.663	1.818	5.556	0.3394	1.505	19.85
	V_3	1.640	1.838	5.807	0.2457	1.323	14.94
	V_4	1.637	1.843	5.839	0.2400	1.318	13.40
	V_e	1.636	1.844	5.842	0.2394	1.336	17.27
δ	V_2	0.06739	0.06049	0.03469	0.1082	0.02774	0.1827
	V_3	0.06628	0.05940	0.03643	0.08236	0.02548	0.1392
	V_4	0.06610	0.05926	0.03665	0.08107	0.02564	0.1257
	V_e	0.06607	0.05916	*0.03669*	0.08144	0.02585	0.1192
R^2	V_2	0.9810	0.9793	0.9957	0.9511	0.9234	0.9747
	V_3	0.9815	0.9789	0.9953	0.9744	0.9408	0.9857
	V_4	0.9816	0.9788	0.9952	0.9756	0.9412	0.9885
	V_e	0.9816	*0.9787*	0.9953	0.9757	0.9396	0.9897

Note: magnitudes a, b, c and σ are accommodated with dimensionalities in [11]

For ammonia and formaldehyde (both kinds of processes), formula V_2 has clearly worse indicators due to the higher order of the described experimental data. For sulphur dioxide and methane, the advantage of formula V_2 is not statistically significant, and for hydrogen sulphide, there is a statistically insignificant advantage of formula V_e. Increased numerical values of empirical coefficients demonstrate the previously marked negative feature of dependence V_2 when describing the curves of high orders.

Thus, the practical application of model (45) also proves its commonality when describing the kinetics of biodestruction of various harmful substances with substrate inhibition of varying intensity. It should be noted that formula (45) is workable technically for any whatever large ranges of concentrations of environmental pollutants.

7. Discussion of results of studying the regularities of biodegradation process with substrate inhibition

The study includes obtaining a full range of theoretical solutions for the dependence of biodestruction rate on substrate concentration and the evidence of the existence in this spectrum of a unified dependence, generally describing the mechanisms of substrate inhibition of varying intensity.

The application of the method of dynamics of averages resulted in obtaining of a full range of theoretical dependences of biodegradation with substrate inhibition. The solution of the spectrum is distinguished by the number of terms of a quickly converging power series in denominators of formulas. The number of terms of the series characterizes the order of the dependence, corresponding to various inhibition intensity, changing from minimal n=2 to limiting n=∞. We detected the proximity of shapes of curves for dependences of specific bio-oxidation rate on concentration of harmful substances for orders from n=3 (V_3) to n=∞ (V_e), and consequently, the essential difference of the dependence of minimum order n=2 (V_2) on other formulas of the range. The value of coordinate of maximum of function V_2 is by 1.42 times higher than in dependence V_3. The results of analysis of the full spectrum of solutions made it possible to determine formulas V_2 and V_e for estimation of their application as generalizing ones and state the sequence of necessary calculations.

To prove the possibilities of using the unified formula in describing the processes of bio-oxidation with substrate inhibition, the method of numerical experiment was applied. Mutual description of various functions from the full range was performed using the least squares method until obtaining the maximum range of the change in argument at the assigned relative error.

At the first stage, the accuracy of description of intermediate dependence V_3 by formulas V_2 and V_e was compared. The obtained data (Table 2) suggests that the range of variation of argument in formula V_e is by 1.5–2 times more in comparison with dependence V_2. This result made it possible to exclude formula V_2 from the candidates to being applied as a generalizing dependence. At this stage, the numerical experiment on description of dependences of other orders V_2, V_3

and V_4 by formula V_e was performed. It follows from the data of Table 3 that formula V_e describes dependence V_2 with 5 % accuracy in the actual range of changes in concentrations of harmful substances. The ratio of the range of a change of argument to the position of maximum is >5 even under conditions of its weak expression.

At the second stage of the numerical experiment, the effect of a random error on the possibility of using a unified formula was simulated. The existence of a random error also leads to a distortion of results when describing experimental data with order $n=2$ by dependence V_2. That is why the influence of a random error on comparative accuracy of description of experimental data with a minimal order of inhibition by formulas V_2 and V_e was modeled. The results of the numerical experiment (Fig. 3, 4) indicate that with an increase in a non-systematic error, the statistical difference between the descriptions by V_2 and V_e continuously decreases up to zero. Convergence is achieved at the ratio of a random error to the initial error that is equal to ≥2.4. This result extends the capabilities of formula V_e when describing actual data of a lower order.

The results of the numerical experiment prove the possibility of using formula V_e as unified during practical calculations of kinetics of the biodegradation process with substrate inhibition of varying intensity. Dependence V_e in its pure form describes the stationary bio-oxidation process without changing the reaction zone and additional arrival of a pollutant in it. The proposed model is not a complete model of a non-stationary process in the bioreactor. The development of such a model requires a separate study. The resulting unified formula is a necessary component of a non-stationary model as the scientific basis for the development of calculation methods and substantiation of project solutions for biochemical treatment plants.

Subsequent improvement of calculation methods also involves assessing the impact of a change in biomass concentration in the biodegradation process.

8. Conclusions

1. Using the method of dynamics of averages, we found a full range of theoretical solutions for dependences of specific bio-oxidation rate V_n on pollutant concentration ρ. Each solution differs by the inhibition intensity expressed by the number of members of quickly converging power series in denominators of equations. The size of the series is determined by the order of a solution, varying from minimal $n=2(V_2)$ to limiting $n\to\infty(V_e)$. The formulas with more than minimal order $n\geq 3$ are characterized by the proximity of the shapes of curves of «specific rate V_n – concentration ρ». The shape of the curve for the solution with minimal order V_2 differs significantly from other dependences of the range. The value of coordinate of the maximum of function V_2 is by 1.42 times higher than that of dependence V_3.

2. Mathematical modeling of physical experiments proved the possibility of the practical use of the solution of limiting order V_e as a unified formula enabling to calculate specific biodegradation rate at any intensity of substrate inhibition. In three series of computational experiments we consistently showed:

– the advantage of formula V_e compared to formula of minimal order V_2 in accuracy of description of experimental data with intermediate intensity of substrate inhibition V_3. The advantage is that the possible range of a change in concentrations at the same relative error is by 1.5–2 times larger;

– guaranteed ensuring 5 % accuracy during the description by formula V_e of experimental data with minimal order V_2 in the actual range of changes in pollutant concentration. The ratio of the maximum range to the coordinate of the position of maximum is always >5;

– convergence, even up to statistical equivalence, of descriptions by extreme dependences of ranges V_2 and V_e of experimental data of minimal order at an increase in a random non-systematic error. Convergence is achieved at the ratio of a random error to the initial description error equal to ≥2.4.

The versatility of the dependence of limiting order V_e is proved by the adequate (determination coefficient $R^2=0.9396–0.9953$) description of empirical data on five harmful substances with varying degrees of inhibition. The existence of biodegradation processes with inhibition intensity of more than minimal $n\geq 3$ was revealed.

References

1. Andrews J. F. A mathematical model for the continuous culture of microorganisms utilizing inhibitory substrates // Biotechnology and Bioengineering. 1968. Vol. 10, Issue 6. P. 707–723. doi: https://doi.org/10.1002/bit.260100602
2. Kinetic Studies on Microbial Activities in Concentrated Solutions / Yano T., Nakahara T., Kamiyama S., Yamada K. // Agricultural and Biological Chemistry. 1966. Vol. 30, Issue 1. P. 42–48. doi: https://doi.org/10.1080/00021369.1966.10858549
3. Yano T., Koga S. Dynamic behavior of the chemostat subject to substrate inhibition // Biotechnology and Bioengineering. 1969. Vol. 11, Issue 2. P. 139–153. doi: https://doi.org/10.1002/bit.260110204
4. Webb J. L. Enzyme and Metabolic Inhibitors. New York: Academic Press, 1963. doi: https://doi.org/10.5962/bhl.title.7320
5. Aiba S., Shoda M., Nagatani M. Kinetics of product inhibition in alcohol fermentation // Biotechnology and Bioengineering. 1968. Vol. 10, Issue 6. P. 845–864. doi: https://doi.org/10.1002/bit.260100610
6. Tseng M. M.,Wayman M. Kinetics of yeast growth: inhibition-threshold substrate concentrations // Canadian Journal of Microbiology. 1975. Vol. 21, Issue 7. P. 994–1003. doi: https://doi.org/10.1139/m75-147
7. Luong J. H. T. Generalization of monod kinetics for analysis of growth data with substrate inhibition // Biotechnology and Bioengineering. 1987. Vol. 29, Issue 2. P. 242–248. doi: https://doi.org/10.1002/bit.260290215
8. Tsuji S., Shimizu K. Performance evaluation of ethanol fermentor systems using a vector-valued objective function // Biotechnology and Bioengineering. 1987. Vol. 30, Issue 3. P. 420–426. doi: https://doi.org/10.1002/bit.260300313
9. Han K., Levenspiel O. Extended monod kinetics for substrate, product, and cell inhibition // Biotechnology and Bioengineering. 1988. Vol. 32, Issue 4. P. 430–447. doi: https://doi.org/10.1002/bit.260320404

10. Edwards V. H. The influence of high substrate concentrations on microbial kinetics // Biotechnology and Bioengineering. 1970. Vol. 12, Issue 5. P. 679–712. doi: https://doi.org/10.1002/bit.260120504
11. Development of universal model of kinetics of bioremediation stationary process with substrate inhibition / Bakhareva A., Shestopalov O., Filenko O., Kobilyansky B. // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 2, Issue 10 (80). P. 19–26. doi: https://doi.org/10.15587/1729-4061.2016.65036
12. Nweke C. O., Okpokwasili G. C. Kinetics of growth and phenol degradation by Pseudomonas Species isolated from petroleum refinery wastewater // International Journal of Biosciences. 2014. Vol. 4, Issue 7. P. 28–37. doi: https://doi.org/10.12692/ijb/4.7.28-37
13. Prifti T., Pinguli L., Malollari I. A comparative study of kinetic immobilized yeast parameters in batch fermentation processes // Europen Journal of Advanced Research in Biological and Life Sciences. 2017. Vol. 5, Issue 3. P. 1–8.
14. Ahmad F. Study of growth kinetic and modeling of ethanol production by Saccharomyces cerevisa // AFRICAN JOURNAL OF BIOTECHNOLOGY. 2011. Vol. 10, Issue 81. doi: https://doi.org/10.5897/ajb11.2763
15. Kinetic Modeling of 1-G Ethanol Fermentations / Olivera S. C., Stremel D. P., Dechechi E. C., Pereira F. M. // Fermentation Processes. 2017. P. 93–117. doi: https://doi.org/10.5772/65460
16. Dutta K. Substrate Inhibition Growth Kinetics for Cutinase Producing Pseudomonas cepacia Using Tomato-peel Extracted Cutin // Chemical and Biochemical Engineering Quarterly. 2015. Vol. 29, Issue 3. P. 437–445. doi: https://doi.org/10.15255/cabeq.2014.2022
17. Comparison of different models of substrate inhibition in aerobic batch biodegradation of malathion / Tazdaït D., Abdi N., Grib H., Lounici H., Pauss A., Mameri N. // Turkish Journal of Engineering and Environmental Sciences. 2013. Vol. 37. P. 221–230. doi: https://doi.org/10.3906/muh-1211-7
18. Kinetic models for nitrogen inhibition in ANAMMOX and nitrification process on deammonification system at room temperature / De Prá M. C., Kunz A., Bortoli M., Scussiato L. A., Coldebella A., Vanotti M., Soares H. M. // Bioresource Technology. 2016. Vol. 202. P. 33–41. doi: https://doi.org/10.1016/j.biortech.2015.11.048
19. Agarry S. E., Audu T. O. K., Solomon B. O. Substrate inhibition kinetics of phenol degradation by Pseudomonas fluorescence from steady state and wash-out data // International Journal of Environmental Science & Technology. 2009. Vol. 6, Issue 3. P. 443–450. doi: https://doi.org/10.1007/bf03326083
20. Kinetic models and parameters estimation study of biomass and ethanol production from inulin by Pichia caribbica (KC977491) / Mounira K. A., Serge H., Nawel O., Radia C., Noreddine K. C. // African Journal of Biotechnology. 2017. Vol. 16, Issue 3. P. 124–131. doi: https://doi.org/10.5897/ajb2016.15747
21. Exploring Kinetics of Phenol Biodegradation by Cupriavidus taiwanesis 187 / Wei Y.-H., Chen W.-C., Chang S.-M., Chen B.-Y. // International Journal of Molecular Sciences. 2010. Vol. 11, Issue 12. P. 5065–5076. doi: https://doi.org/10.3390/ijms11125065
22. Halmi M. I. E., Shukor M. S., Shukor M. Y. Evoluation of several mathematical models for fitting the growth and kinetics of the Catechol-degrading Candida parapsilopsis: part 2 // Journal of Environmental Bioremediation and Toxicology. 2014. Vol. 2, Issue 2. P. 53–57.
23. Day S., Mukherjee S. A study of the kinetic coefficients and the rate of biodegradation of phenol by indigenous mixed microbial system // African Journal of Water Conservation and Sustainability. 2014. Vol. 2, Issue 1. P. 099–107.
24. Chakraborty B., Ray L., Basu S. Study of phenol biodegradation by an indigenous mixed consortium of bacteria // Indian Journal of Chemical Technology. 2015. Vol. 22, Issue 5. P. 227–233.
25. Biodegradation of Ammonium Ions and Formate During Ammonium Formate Metabolism by Yarrowia lipolytica and Pichia guilliermondii in a Batch Reactor / Nsoe M. N., Kofa G. P., Ndi K. S., Mohammadou B., Heran M., Kayem G. J. // Water, Air, & Soil Pollution. 2018. Vol. 229, Issue 5. doi: https://doi.org/10.1007/s11270-018-3795-0
26. Deriase S. F., Younis S. A., El-Gendy N. S. Kinetic evaluation and modeling for batch degradation of 2-hydroxybiphenyl and 2,2′-dihydroxybiphenyl byCorynebacterium variabilisSh42 // Desalination and Water Treatment. 2013. Vol. 51, Issue 22-24. P. 4719–4728. doi: https://doi.org/10.1080/19443994.2012.744950
27. Raghuvanshi S., Gupta S. Growth kinetics of acclimated mixed culture for degradation of Isopropyl Alcohol (IPA) // Journal of Biotechnology and Biomaterials. 2012. Vol. s13. doi: https://doi.org/10.4172/2155-952x.s13-002
28. Dey S., Mukherjee S. Kinetic modelling for removal of m -cresol from wastewater using mixed microbial culture in batch reactor // Journal of Water Reuse and Desalination. 2012. Vol. 2, Issue 3. P. 149–156. doi: https://doi.org/10.2166/wrd.2012.055
29. Taho Hemdi A. Vvedenie v issledovanie operaciy: monografiya. Moscow, Sankt-Peterburg, Kyiv: Izdatel'skiy dom «Vil'yams», 2001. 912 p.
30. Keleti T. Osnovy fermentativnoy kinetiki: monografiya. Moscow: Mir, 1990. 350 p.
31. Tikhonov A. N. Systems of differential equations containing small parameters in the derivatives // Matematicheskiy sbornik. 1952. Vol. 31, Issue 3. P. 575–586. URL: http://www.mathnet.ru/links/672ece88e3cd9c1c4e2f0a144ca1951e/sm5548.pdf
32. Romanovskiy Yu. M., Stepanova N. V., Chernavskiy D. S. Matematicheskoe modelirovanie v biofizike: monografiya. Moscow, Izhevsk: Institut komp'yuternyh issledovaniy, 2003. 402 p.

ABSTRACT AND REFERENCES

ECOLOGY

DOI: 10.15587/1729-4061.2019.166571

CONSTRUCTION OF A GENERALIZED MODEL OF THE HARMFUL SUBSTANCES BIOCHEMICAL DESTRUCTION PROCESS KINETICS UNDER CONDITIONS OF SUBSTRATE INHIBITION USING THE METHODS OF SIMULATION MODELING (p. 6–16)

Ganna Bakharieva
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0003-0765-9943

Tetiana Falalieieva
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0003-0021-4917

Serhii Petrov
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0001-6500-5310

Iryna Mezentseva
National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0001-7695-7982

Borys Kobylianskyi
Teaching and Research Professional Pedagogical Institute of Ukrainian Engineering and Pedagogical Academy, Bakhmut, Ukraine
ORCID: http://orcid.org/0000-0003-3226-5997

Ihor Tolkunov
National University of Civil Defense of Ukraine, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0001-5129-3120

Oleksandr Bondarenko
National University of Civil Defense of Ukraine, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-7544-3442

For the purpose of obtaining the complete range of solutions for substrate inhibition of varying intensity, the mechanism of enzyme kinetics in a biocell was modeled by a multi-channel queuing system. A full range of solutions is required to make a well-grounded choice of a unified generalizing formula. The process of biodegradation with substrate inhibition was described mathematically using the method of dynamics of averages. For specific destruction rate, a full range of solutions V_n of the system from minimum $n=2$ to limiting $n\to\infty$ order was found. It was established that the parameters of the curve shape for the solution with minimum inhibition intensity V_2 substantially stand out from the general series of the spectrum formulas. The value of the coordinate of function maximum ($n=2$) V_2 is by 1.42 times higher than that of dependence ($n=3$) V_3.

In the numerical experiment, the physical test was simulated by description with the help of the method of the least squares of the data, assigned by the calculation from the formulas of different structures, bearing in mind a sporadic random error. The series of numerical experiments demonstrated the capability of the formula of limiting order formula V_e to describe the dependences of the whole spectrum of solutions. During describing the intermediate ratio V_3 with the help of formulas V_2 and V_e, the benefit is the possible range of changing the concentrations, which is by 1.5–2 times larger at the same relative error for dependence V_e. For critical minimal order, an average relative error is sure not to exceed five percent. An increase in random error always result in statistical equality, in accuracy of describing by formulas of minimal V_2 and limiting orders V_e of the data, assigned by calculation of second-order dependences. Statistical equality is achieved at the ratio of a random error to the initial error equal to ≥2.4.

Collectively, the importance of the results of numerical modeling of a physical experiment involves proving the possibility of using the formula of limiting order V_e as unified when describing the biodegradation processes with different mechanisms of substrate inhibition. This conclusion is proved by the adequate ($R^2=0.9396–0.9953$) description with the help of the dependence of limiting order of experimental data on five harmful substances with varying inhibition degrees. A large amount of calculation allowed achieving a definite result – we obtained the unified formula that makes it possible to proceed to scientifically grounded design calculations for bio-treatment plants.

Keywords: biodegradation, substrate inhibition, queuing system, numerical experiment, unified formula.

References

1. Andrews, J. F. (1968). A mathematical model for the continuous culture of microorganisms utilizing inhibitory substrates. Biotechnology and Bioengineering, 10 (6), 707–723. doi: https://doi.org/10.1002/bit.260100602
2. Yano, T., Nakahara, T., Kamiyama, S., Yamada, K. (1966). Kinetic Studies on Microbial Activities in Concentrated Solutions. Agricultural and Biological Chemistry, 30 (1), 42–48. doi: https://doi.org/10.1080/00021369.1966.10858549
3. Yano, T., Koga, S. (1969). Dynamic behavior of the chemostat subject to substrate inhibition. Biotechnology and Bioengineering, 11 (2), 139–153. doi: https://doi.org/10.1002/bit.260110204
4. Webb, J. L. (1963). Enzyme and Metabolic Inhibitors. New York: Academic Press. doi: https://doi.org/10.5962/bhl.title.7320
5. Aiba, S., Shoda, M., Nagatani, M. (1968). Kinetics of product inhibition in alcohol fermentation. Biotechnology and Bioengineering, 10 (6), 845–864. doi: https://doi.org/10.1002/bit.260100610
6. Tseng, M. M.,Wayman, M. (1975). Kinetics of yeast growth: inhibition-threshold substrate concentrations. Canadian Journal of Microbiology, 21 (7), 994–1003. doi: https://doi.org/10.1139/m75-147
7. Luong, J. H. T. (1987). Generalization of monod kinetics for analysis of growth data with substrate inhibition. Biotechnology and Bioengineering, 29 (2), 242–248. doi: https://doi.org/10.1002/bit.260290215
8. Tsuji, S., Shimizu, K. (1987). Performance evaluation of ethanol fermentor systems using a vector-valued objective function. Biotechnology and Bioengineering, 30 (3), 420–426. doi: https://doi.org/10.1002/bit.260300313
9. Han, K., Levenspiel, O. (1988). Extended monod kinetics for substrate, product, and cell inhibition. Biotechnology and Bioengineering, 32 (4), 430–447. doi: https://doi.org/10.1002/bit.260320404
10. Edwards, V. H. (1970). The influence of high substrate concentrations on microbial kinetics. Biotechnology and Bioengineering, 12 (5), 679–712. doi: https://doi.org/10.1002/bit.260120504
11. Bakhareva, A., Shestopalov, O., Filenko, O., Kobilyansky, B. (2016). Development of universal model of kinetics of bioremediation stationary process with substrate inhibition. Eastern-European Journal of Enterprise Technologies, 2 (10 (80)), 19–26. doi: https://doi.org/10.15587/1729-4061.2016.65036
12. Nweke, C. O., Okpokwasili, G. C. (2014). Kinetics of growth and phenol degradation by Pseudomonas Species isolated from petroleum refinery wastewater. International Journal of Biosciences, 4 (7), 28–37. doi: https://doi.org/10.12692/ijb/4.7.28-37

13. Prifti, T., Pinguli, L., Malollari, I. (2017). A comparative study of kinetic immobilized yeast parameters in batch fermentation processes. Europen Journal of Advanced Research in Biological and Life Sciences, 5 (3), 1–8.
14. Ahmad, F. (2011). Study of growth kinetic and modeling of ethanol production by Saccharomyces cerevisa. AFRICAN JOURNAL OF BIOTECHNOLOGY, 10 (81). doi: https://doi.org/10.5897/ajb11.2763
15. Olivera, S. C., Stremel, D. P., Dechechi, E. C., Pereira, F. M. (2017). Kinetic Modeling of 1-G Ethanol Fermentations. Fermentation Processes, 93–117. doi: https://doi.org/10.5772/65460
16. Dutta, K. (2015). Substrate Inhibition Growth Kinetics for Cutinase Producing Pseudomonas cepacia Using Tomato-peel Extracted Cutin. Chemical and Biochemical Engineering Quarterly, 29 (3), 437–445. doi: https://doi.org/10.15255/cabeq.2014.2022
17. Tazdaït, D., Abdi, N., Grib, H., Lounici, H., Pauss, A., Mameri, N. (2013). Comparison of different models of substrate inhibition in aerobic batch biodegradation of malathion. Turkish Journal of Engineering and Environmental Sciences, 37, 221–230. doi: https://doi.org/10.3906/muh-1211-7
18. De Prá, M. C., Kunz, A., Bortoli, M., Scussiato, L. A., Coldebella, A., Vanotti, M., Soares, H. M. (2016). Kinetic models for nitrogen inhibition in ANAMMOX and nitrification process on deammonification system at room temperature. Bioresource Technology, 202, 33–41. doi: https://doi.org/10.1016/j.biortech.2015.11.048
19. Agarry, S. E., Audu, T. O. K., Solomon, B. O. (2009). Substrate inhibition kinetics of phenol degradation by Pseudomonas fluorescence from steady state and wash-out data. International Journal of Environmental Science & Technology, 6 (3), 443–450. doi: https://doi.org/10.1007/bf03326083
20. Mounira, K. A., Serge, H., Nawel, O., Radia, C., Noreddine, K. C. (2017). Kinetic models and parameters estimation study of biomass and ethanol production from inulin by Pichia caribbica (KC977491). African Journal of Biotechnology, 16 (3), 124–131. doi: https://doi.org/10.5897/ajb2016.15747
21. Wei, Y.-H., Chen, W.-C., Chang, S.-M., Chen, B.-Y. (2010). Exploring Kinetics of Phenol Biodegradation by Cupriavidus taiwanesis 187. International Journal of Molecular Sciences, 11 (12), 5065–5076. doi: https://doi.org/10.3390/ijms11125065
22. Halmi, M. I. E., Shukor, M. S., Shukor, M. Y. (2014). Evoluation of several mathematical models for fitting the growth and kinetics of the Catechol-degrading Candida parapsilopsis: part 2. Journal of Environmental Bioremediation and Toxicology, 2 (2), 53–57.
23. Day, S., Mukherjee, S. (2014). A study of the kinetic coefficients and the rate of biodegradation of phenol by indigenous mixed microbial system. African Journal of Water Conservation and Sustainability, 2 (1), 099–107.
24. Chakraborty, B., Ray, L., Basu, S. (2015). Study of phenol biodegradation by an indigenous mixed consortium of bacteria. Indian Journal of Chemical Technology, 22 (5), 227–233.
25. Nsoe, M. N., Kofa, G. P., Ndi, K. S., Mohammadou, B., Heran, M., Kayem, G. J. (2018). Biodegradation of Ammonium Ions and Formate During Ammonium Formate Metabolism by Yarrowia lipolytica and Pichia guilliermondii in a Batch Reactor. Water, Air, & Soil Pollution, 229 (5). doi: https://doi.org/10.1007/s11270-018-3795-0
26. Deriase, S. F., Younis, S. A., El-Gendy, N. S. (2013). Kinetic evaluation and modeling for batch degradation of 2-hydroxybiphenyl and 2,2′-dihydroxybiphenyl byCorynebacterium variabilisSh42. Desalination and Water Treatment, 51 (22-24), 4719–4728. doi: https://doi.org/10.1080/19443994.2012.744950
27. Raghuvanshi, S., Gupta, S. (2012). Growth kinetics of acclimated mixed culture for degradation of Isopropyl Alcohol (IPA). Journal of Biotechnology and Biomaterials, s13. doi: https://doi.org/10.4172/2155-952x.s13-002
28. Dey, S., Mukherjee, S. (2012). Kinetic modelling for removal of *m*-cresol from wastewater using mixed microbial culture in batch reactor. Journal of Water Reuse and Desalination, 2 (3), 149–156. doi: https://doi.org/10.2166/wrd.2012.055
29. Taho Hemdi, A. (2001). Vvedenie v issledovanie operaciy. Moscow, Sankt-Peterburg, Kyiv: Izdatel'skiy dom «Vil'yams», 912.
30. Keleti, T. (1990). Osnovy fermentativnoy kinetiki. Moscow: Mir, 350.
31. Tikhonov, A. N. (1952). Systems of differential equations containing small parameters in the derivatives. Matematicheskiy sbornik, 31 (3), 575–586. Available at: http://www.mathnet.ru/links/672ece88e3cd9c1c4e2f0a144ca1951e/sm5548.pdf
32. Romanovskiy, Yu. M., Stepanova, N. V., Chernavskiy, D. S. (2003). Matematicheskoe modelirovanie v biofizike. Moscow, Izhevsk: Institut komp'yuternyh issledovaniy, 402.

DOI: 10.15587/1729-4061.2019.170200

USE OF FLY ASH FOR CONDITIONING THE EXCESS ACTIVATED SLUDGE DURING DELIQUEFACTION AT CHAMBER-MEMBRANE FILTER PRESSES (p. 17–23)

Oleh Zlatkovskyi
PRODEKO-ELK Sp.zo.o., Elk, Poland
ORCID: http://orcid.org/0000-0002-2350-5955

Andrii Shevchenko
PRODEKO-ELK Sp.zo.o., Elk, Poland
ORCID: http://orcid.org/0000-0002-9576-282X

Tamara Shevchenko
O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
ORCID: http://orcid.org/0000-0002-4513-6759

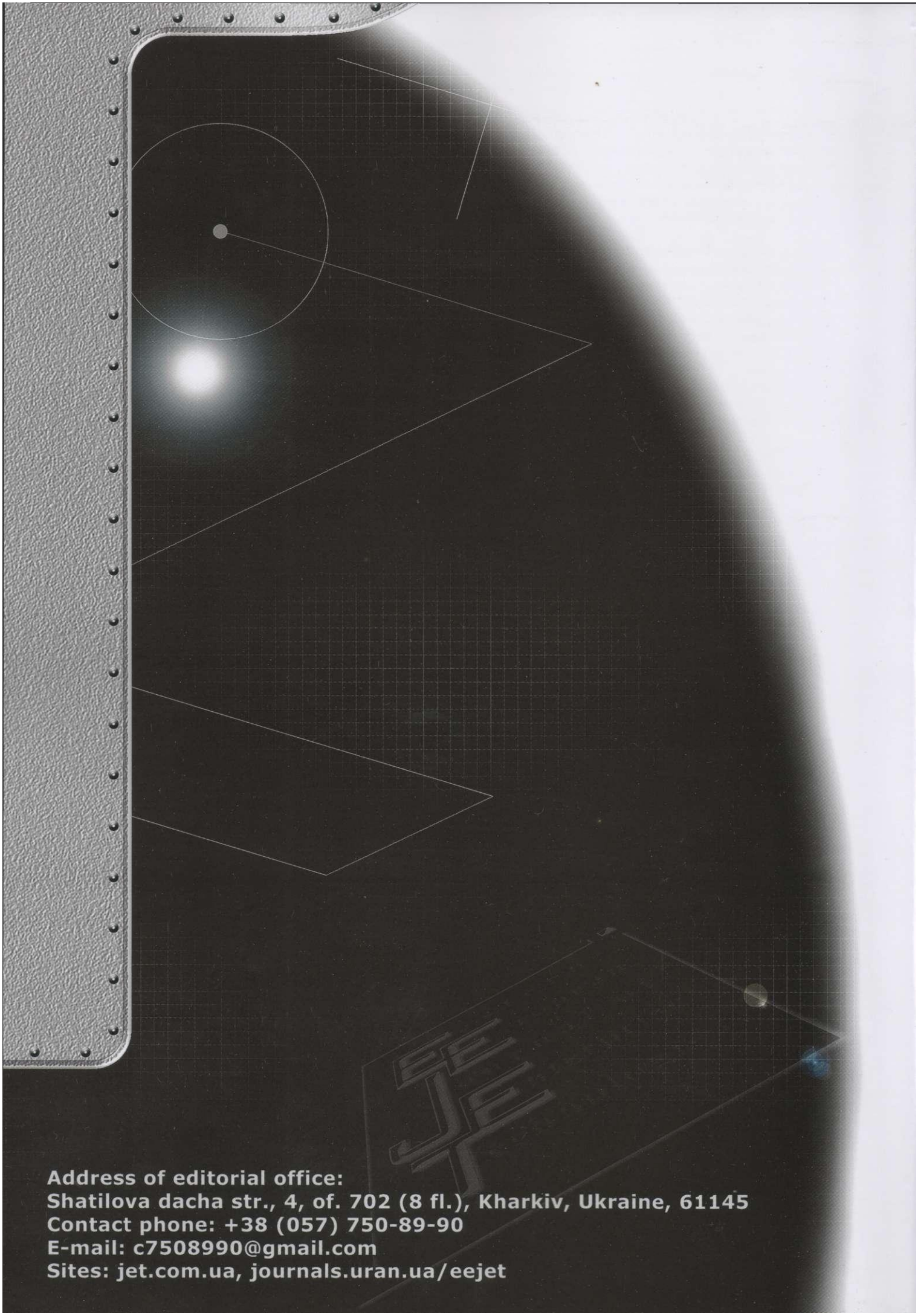
Results of experimental studies of deliquefaction of excess activated sludge from municipal wastewater treatment facilities in chamber-membrane filter presses were presented. To condition the sludge, fly ash from thermal power plants was added as a mineral additive. Experimental studies have shown high efficiency of deliquefaction of the excess activated sludge with addition of fly ash. Increase in the dose of fly ash has led to an overall increase in filtration capacity and a decrease in moisture content in the filter cake. It was found that in the case of adding fly ash in an amount of 2 wt. % of the initial sludge, deliquefaction efficiency did not increase significantly. In this case, filtering time was reduced only by 15 % and specific capacity increased by 12 %. In the case of increasing the proportion of fly ash to 6 wt. % of initial sludge, a more intensive acceleration of the process was observed. Filtering duration was reduced from 100 to 10 min, specific capacity increased from 87 to 400 l/m^2·hr.

Experimental studies have shown that addition of fly ash to sediments of municipal wastewater treatment facilities as a mineral component provides the possibility of deliquefaction of the suspensions obtained using a chamber-membrane filter press. With optimal doses of 4–5 wt. % of the mass of initial sludge, filter capacity is expected to be 350–400 l/m^2·hr. The resulting filter cake had moisture content of about 60 %, a dense, dry structure making it possible to transport it in bulk.

Keywords: chamber-membrane filter press, conditioning, fly ash, deliquefaction, filtering duration, activated sludge.

References

1. Sizykh, M. R. (2013). Conditioning of sewage sludge. Vestnik Buryatskogo gosudarstvennogo universiteta, 3, 17–19.
2. Wójcik, M., Stachowicz, F., Masłoń, A. (2017). The Possibility of Sewage Sludge Conditioning and Dewatering with the Use of Bio-



Address of editorial office:
Shatilova dacha str., 4, of. 702 (8 fl.), Kharkiv, Ukraine, 61145
Contact phone: +38 (057) 750-89-90
E-mail: c7508990@gmail.com
Sites: jet.com.ua, journals.uran.ua/eejet