MECHANICS

DOI: 10.15587/2706-5448.2025.323751

FINITE ELEMENT MODELING OF COMPOSITE BIOMECHANICAL STRUCTURES: ANALYSIS OF THE LUMBO-PELVIS AND CRANIAL-MAXILLOFACIAL COMPLEXES

pages 6–14

Andrii Kondratiev, *Doctor of Technical Sciences, Professor, Head of Department of Materials Science and Engineering of Composite Structures, O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine; Visiting Researcher, Department of Engineering, University of Cambridge, Cambridge, United Kingdom, e-mail: andrii.kondratiev@kname.edu.ua, ORCID: https://orcid.org/0000-0002-8101-1961*

The object of this study is human biomechanical systems in both normal and pathological conditions, focusing on the lumbo-pelvic and craniofacial complexes, including restorative structures such as miniplates, screws, and dental implants. The military actions caused by Russian aggression against Ukraine have prompted the development of more effective methods for injury treatment and rehabilitation.

This research proposes novel digital modelling methods for biomechanical systems that incorporate individual mechanical properties of biological tissues and enable a comprehensive stress-strain analysis under normal conditions, pathological changes, and post-reconstructive states. The study utilizes finite element analysis (FEA) and computer simulation, integrated with CT and MRI data, ensuring high accuracy in predicting the functional behaviour of biological tissues. The dominant biomechanical factors that help prevent mechanical overload of tissues and reduce the risk of complications have been identified. The study investigates the kinematic chain "lumbar spine – sacroiliac joint – pelvis", assessing the impact of pathological variations in lumbar lordosis and sacral inclination angle. For the craniofacial complex, the research examines the biomechanical conditions for successful osseointegration of miniplates, screws, and implants in jaw reconstruction.

The practical applications of the obtained results include orthopedics, traumatology, dentistry, and rehabilitation medicine. The proposed methods contribute to improving surgical planning accuracy, optimizing rehabilitation procedures, and developing durable implants adapted to the patient's anatomical features. This will help minimize the risk of complications and accelerate patient recovery.

Keywords: biomechanical system modelling, finite element analysis, digital simulation, stress-strain state, osseointegration, kinematic analysis, computational biomechanics of biological tissues.

References

1. El-Tallawy, S. N., Nalamasu, R., Salem, G. I., LeQuang, J. A. K., Pergolizzi, J. V., Christo, P. J. (2021). Management of Musculoskeletal Pain: An Update with Emphasis on Chronic Musculoskeletal Pain. *Pain and Therapy, 10 (1),* 181–209. https://doi.org/10.1007/s40122-021-00235-2
2. Urits, I., Burshtein, A., Sharma, M., Testa, L., Gold, P. A., Orhurhu, V. et al. (2019). Low Back Pain, a Comprehensive Review: Pathophysiology, Diagnosis, and Treatment. *Current Pain and Headache Reports, 23 (3).* https://doi.org/10.1007/s11916-019-0757-1
3. Zhang, Q., Chon, T., Zhang, Y., Baker, J. S., Gu, Y. (2021). Finite element analysis of the lumbar spine in adolescent idiopathic scoliosis subjected to different loads. *Computers in Biology and Medicine, 136,* 104745. https://doi.org/10.1016/j.compbiomed.2021.104745
4. Azadi, A., Arjmand, N. (2021). A comprehensive approach for the validation of lumbar spine finite element models investigating post-fusion adjacent segment effects. *Journal of Biomechanics, 121,* 110430. https://doi.org/10.1016/j.jbiomech.2021.110430
5. Umale, S., Yoganandan, N., Kurpad, S. N. (2020). Development and validation of osteoligamentous lumbar spine under complex loading conditions: A step towards patient-specific modeling. *Journal of the Mechanical Behavior of Biomedical Materials, 110,* 103898. https://doi.org/10.1016/j.jmbbm.2020.103898
6. Xu, M., Yang, J., Lieberman, I. H., Haddas, R. (2016). Lumbar spine finite element model for healthy subjects: development and validation. *Computer Methods in Biomechanics and Biomedical Engineering, 20 (1),* 1–15. https://doi.org/10.1080/10255842.2016.1193596
7. Eremina, G., Smolin, A., Xie, J., Syrkashev, V. (2022). Development of a Computational Model of the Mechanical Behavior of the L4–L5 Lumbar Spine: Application to Disc Degeneration. *Materials, 15 (19),* 6684. https://doi.org/10.3390/ma15196684
8. Areias, B., Caetano, S. C., Sousa, L. C., Parente, M., Jorge, R. N., Sousa, H., Gonçalves, J. M. (2020). Numerical simulation of lateral and transforaminal lumbar interbody fusion, two minimally invasive surgical approaches. *Computer Methods in Biomechanics and Biomedical Engineering, 23 (8),* 408–421. https://doi.org/10.1080/10255842.2020.1734579
9. Más, Y., Gracia, L., Ibarz, E., Gabarre, S., Peña, D., Herrera, A. (2017). Finite element simulation and clinical follow-up of lumbar spine biomechanics with dynamic fixations. *PLOS ONE, 12 (11),* e0188328. https://doi.org/10.1371/journal.pone.0188328
10. Skrypa, O. L., Bandrivsky, Y. L. (2020). Determining the frequency of functional disorders of the TMJ in patients with mandible fractures depending on the location. *Wiadomości Lekarskie, 73 (2),* 245–249. https://doi.org/10.36740/wlek202002107
11. Yamamoto, K., Matsusue, Y., Horita, S., Murakami, K., Sugiura, T., Kirita, T. (2019). Maxillofacial Fractures Associated With Interpersonal Violence. *Journal of Craniofacial Surgery, 30 (4),* e312–e315. https://doi.org/10.1097/scs.0000000000005306
12. Stanford-Moore, G., Murr, A. H. (2022). Mandibular Angle Fractures. *Facial Plastic Surgery Clinics of North America, 30 (1),* 109–116. https://doi.org/10.1016/j.fsc.2021.08.009
13. Mathew, N., Singh, I., Gandhi, S., Solanki, M., Bedi, N. S. (2020). The Efficacy of Fixation of Unilateral Mandibular Angle Fracture with Single 3D Plate vs Single Miniplate Using Transbuccal Approach. *Journal of Maxillofacial and Oral Surgery, 21 (2),* 405–412. https://doi.org/10.1007/s12663-020-01465-1
14. Meslier, Q. A., Shefelbine, S. J. (2023). Using Finite Element Modeling in Bone Mechanoadaptation. *Current Osteoporosis Reports, 21 (2),* 105–116. https://doi.org/10.1007/s11914-023-00776-9
15. Prasadh, S., Krishnan, A. V., Lim, C. Y. H., Gupta, M., Wong, R. (2022). Titanium versus magnesium plates for unilateral mandibular angle fracture fixation: biomechanical evaluation using 3-dimensional finite element analysis. *Journal of Materials Research and Technology, 18,* 2064–2076. https://doi.org/10.1016/j.jmrt.2022.03.111
16. Orassi, V., Duda, G. N., Heiland, M., Fischer, H., Rendenbach, C., Checa, S. (2021). Biomechanical Assessment of the Validity of Sheep as a Preclinical Model for Testing Mandibular Fracture Fixation Devices. *Frontiers in Bioengineering and Biotechnology, 9.* https://doi.org/10.3389/fbioe.2021.672176
17. Kurakar, M., Joshi, U. (2021). Comparative Study of Miniplate vs Reconstruction Plate in the Management of Bilateral Parasymphysis Mandible Fracture: FEM Analysis. *Journal of Maxillofacial and Oral Surgery, 22 (1),* 9–17. https://doi.org/10.1007/s12663-021-01649-3
18. Snyder, E., Trabia, M., Trabelsi, N. (2022). An approach for simultaneous reduction and fixation of mandibular fractures. *Computer Methods in Biomechanics and Biomedical Engineering, 26 (9),* 1064–1076. https://doi.org/10.1080/10255842.2022.2105143
19. Overmann, A. L., Aparicio, C., Richards, J. T., Mutreja, I., Fischer, N. G., Wade, S. M. et al. (2020). Orthopaedic osseointegration: Implantology and future directions. *Journal of Orthopaedic Research, 38 (7),* 1445–1454. https://doi.org/10.1002/jor.24576
20. Mao, B., Tian, Y., Wang, C., Liu, D., Zhou, Y., Li, J. (2023). The application of optimization design in stomatology: A literature review. *Medicine in Novel Technology and Devices, 19,* 100252. https://doi.org/10.1016/j.medntd.2023.100252
21. Guha, I., Zhang, X., Rajapakse, C. S., Chang, G., Saha, P. K. (2022). Finite element analysis of trabecular bone microstructure using CT imaging and continuum

ISSN-L 2664-9969; E-ISSN 2706-5448

mechanical modeling. *Medical Physics, 49 (6),* 3886–3899. https://doi.org/10.1002/mp.15629

22. Golovanevskiy, V., Kondratiev, A. (2021). Elastic Properties of Steel-Cord Rubber Conveyor Belt. *Experimental Techniques, 45 (2),* 217–226. https://doi.org/10.1007/s40799-021-00439-3
23. Li, J., Jansen, J. A., Walboomers, X. F., van den Beucken, J. JJP. (2020). Mechanical aspects of dental implants and osseointegration: A narrative review. *Journal of the Mechanical Behavior of Biomedical Materials, 103,* 103574. https://doi.org/10.1016/j.jmbbm.2019.103574
24. Barua, S. L., Poduval, T. S., Rani, S., Jain, N., Thakur, S. (2023). Stress distribution in bone around an implant-supported three-unit fixed dental prosthesis using two different computer-aided designing/computer-aided milling provisional crown materials: Milled polymethylmethacrylate and milled polyetheretherketone – A finite element analysis. *Dental Research Journal, 20 (1).* https://doi.org/10.4103/1735-3327.372650
25. Qiu, P., Cao, R., Li, Z., Fan, Z. (2024). A comprehensive biomechanical evaluation of length and diameter of dental implants using finite element analyses: A systematic review. *Heliyon, 10 (5),* e26876. https://doi.org/10.1016/j.heliyon.2024.e26876
26. Kondratiev, A., Demenko, V., Linetskiy, I., Weisskircher, H.-W., Linetska, L. (2024). Evaluation of Bone Turnover around Short Finned Implants in Atrophic Posterior Maxilla: A Finite Element Study. *Prosthesis, 6 (5),* 1170–1188. https://doi.org/10.3390/prosthesis6050084
27. Pjetursson, B., Fehmer, V., Sailer, I. (2022). EAO Position Paper: Material Selection for Implant-Supported Restorations. *The International Journal of Prosthodontics, 35 (1),* 7–16. https://doi.org/10.11607/ijp.8013
28. Linetskiy, I., Sutcliffe, M., Kondratiev, A., Demenko, V., Linetska, L., Yefremov, O. (2023). A Novel Method of Load Bearing Ability Analysis of Short Plateau Implants Placed in Compromised Bone. *2023 IEEE 4th KhPI Week on Advanced Technology (KhPIWeek),* 1–6. https://doi.org/10.1109/khpiweek61412.2023.10312831
29. Gontarovskyi, P., Smetankina, N., Garmash, N., Melezhyk, I. (2021). Numerical Analysis of Stress-Strain State of Fuel Tanks of Launch Vehicles in 3D Formulation. *Integrated Computer Technologies in Mechanical Engineering – 2020,* 609–619. https://doi.org/10.1007/978-3-030-66717-7_52
30. Gerlici, J., Lovska, A., Pavliuchenkov, M. (2024). Study of the Dynamics and Strength of the Detachable Module for Long Cargoes under Asymmetric Loading Diagrams. *Applied Sciences, 14 (8),* 3211. https://doi.org/10.3390/app14083211
31. Sagin, S., Kuropyatnyk, O., Sagin, A., Tkachenko, I., Fomin, O., Píštěk, V., Kučera, P. (2022). Ensuring the Environmental Friendliness of Drillships during Their Operation in Special Ecological Regions of Northern Europe. *Journal of Marine Science and Engineering, 10 (9),* 1331. https://doi.org/10.3390/jmse10091331
32. Lisiak-Myszke, M., Marciniak, D., Bieliński, M., Sobczak, H., Garbacewicz, Ł., Drogoszewska, B. (2020). Application of Finite Element Analysis in Oral and Maxillofacial Surgery – A Literature Review. *Materials, 13 (14),* 3063. https://doi.org/10.3390/ma13143063
33. Matos, J. D. M. de, Queiroz, D. A., Nakano, L. J. N., Andrade, V. C., Ribeiro, N. de C. R., Borges, A. L. S. et al. (2022). Bioengineering Tools Applied to Dentistry: Validation Methods for In Vitro and In Silico Analysis. *Dentistry Journal, 10 (8),* 145. https://doi.org/10.3390/dj10080145
34. Xie, B., Zhang, L., Wang, Y., Chu, Y., Lu, Y. (2024). Finite element analysis in the Dental Sciences: A Bibliometric and a Visual Study. *International Dental Journal.* https://doi.org/10.1016/j.identj.2024.08.005
35. Kondratiev, A., Smetankina, N., Staude, V. (2024). Biomechanical Analysis of Stress-Strain Distribution in the Lumbar Spine-Sacrum-Pelvis System with Emphasis on Sacroiliac Joint Dysfunction. *Prosthesis, 7 (1),* 4. https://doi.org/10.3390/prosthesis7010004
36. Ogurkowska, M. B., Błaszczyk, A. (2020). Distribution of Young's modulus at various sampling points in a human lumbar spine vertebral body. *The Spine Journal, 20 (11),* 1861–1875. https://doi.org/10.1016/j.spinee.2020.06.013
37. Müller, A., Rockenfeller, R., Damm, N., Kosterhon, M., Kantelhardt, S. R., Aiyangar, A. K., Gruber, K. (2021). Load Distribution in the Lumbar Spine During Modeled Compression Depends on Lordosis. *Frontiers in Bioengineering and Biotechnology, 9.* https://doi.org/10.3389/fbioe.2021.661258
38. Kondratiev, A., Sutcliffe, M., Demenko, V., Linetskiy, I., Yefremov, O., Linetska, L. (2024). Efficiency of Miniplates Fixation in Mandibular Oblique Fractures. *2024 IEEE 5th KhPI Week on Advanced Technology (KhPIWeek),* 1–6. https://doi.org/10.1109/khpiweek61434.2024.10878063
39. Alaneme, K. K., Kareem, S. A., Ozah, B. N., Alshahrani, H. A., Ajibuwa, O. A. (2022). Application of finite element analysis for optimizing selection and design of Ti-based biometallic alloys for fractures and tissues rehabilitation: a review. *Journal of Materials Research and Technology, 19,* 121–139. https://doi.org/10.1016/j.jmrt.2022.05.001
40. Kuritsyn, A., Taranenko, I., Miroshnikov, V., Demenko, V., Kondratiev, A. (2024). Regression Analysis of Geometric Parameters of "Screw Implant – Maxillary Segment" Biomechanical System. *Integrated Computer Technologies in Mechanical Engineering – 2023,* 235–246. https://doi.org/10.1007/978-3-031-61415-6_20
41. Perren, S. M. (1979). Physical and biological aspects of fracture healing with special reference to internal fixation. *Clinical Orthopaedics and Related Research, 138,* 175–196.

MECHANICAL ENGINEERING TECHNOLOGY

DOI: 10.15587/2706-5448.2025.323779

STUDY OF STATOR SLOT CONFIGURATION AND COIL DIAMETER ON BLDC MOTOR EFFICIENCY AND STABILITY

pages 15–20

Sugeng Hadi Susilo, *Doctor of Engineering, Associate Professor, Department of Mechanical Engineering, State Polytechnic of Malang, Malang, Indonesia, e-mail: sugeng.hadi@polinema.ac.id, ORCID: https://orcid.org/0000-0003-3077-2039*

Eko Yudiyanto, *Doctor of Engineering, Associate Professor, Department of Mechanical Engineering, State Polytechnic of Malang, Malang, Indonesia, ORCID: https://orcid.org/0000-0002-7675-3629*

Fatkhur Rohman, *Assistant Professor, Department of Electronic Engineering, State Polytechnic of Malang, Malang, Indonesia, ORCID: https://orcid.org/0000-0002-1050-0274*

Wirawan, *Doctor of Engineering, Assistant Professor, Department of Mechanical Engineering, State Polytechnic of Malang, Malang, Indonesia, ORCID: https://orcid.org/0000-0001-7168-2967*

Satworo Adiwidodo, *Doctor of Engineering, Assistant Professor, Department of Mechanical Engineering, State Polytechnic of Malang, Malang, Indonesia, ORCID: https://orcid.org/0000-0002-4774-6438*

Muhammad Arif Nur Huda, *Lecturer, Department of Mechanical Engineering, State Polytechnic of Malang, Malang, Indonesia, ORCID: https://orcid.org/0009-0004-9038-3486*

Bakti Indra Kurniawan, *Lecturer, Department of Electrical Engineering, State Polytechnic of Malang, Malang, Indonesia, ORCID: https://orcid.org/0009-0005-1949-9870*

Dwi Pebrianti, *Doctor of Engineering, Associate Professor, Department of Mechanical and Aerospace Engineering, International Islamic University Malaysia, Selangor, Malaysia, ORCID: https://orcid.org/0000-0001-9938-5219*

Mohammad Fadhil Bin Abas, *Doctor of Engineering, Associate Professor, Department of Electrical and Electronic Engineering Technology, University of Malaysia Pahang, Pahang, Malaysia, ORCID: https://orcid.org/0000-0001-9480-4357*

The object of research is the axial flux BLDC (Brushless DC) motor, widely used in electric vehicles and industrial applications due to its compact design and high efficiency. One of the most problematic areas is optimizing the stator slot configuration and coil diameter to enhance efficiency and stability. Previous studies show that these parameters significantly affect magnetic field distribution, losses, and overall performance. However, a systematic investigation is still needed. Therefore, this study aims to identify optimal parameters to improve BLDC motor efficiency and stability.

In the course of the study, an experimental setup with a BLDC motor, controller, power supply, and measurement tool were used. The motor was tested with different stator slots (12 and 24) and coil diameters (0.2 mm, 0.5 mm, 0.7 mm). Measurements included power, current, speed, and temperature. Data analysis assessed the impact on efficiency and stability, supported by numerical simulations for validation and optimization.

Received results show that increasing stator slots from 12 to 24 improves magnetic field distribution and motor efficiency, with power output reaching 3060 W in the optimal configuration. This is due to the proposed stator slot variation, which reduces magnetic losses and enhances thermal efficiency. In particular, motors with 24 slots and a 0.5 mm coil diameter achieved the highest efficiency, while a 0.7 mm coil led to performance decline due to increased resistance. The findings highlight the need for an optimal balance between coil diameter and stator slot configuration for stable and efficient operation.

This ensures the development of high-performance BLDC motors with improved efficiency and stability. Compared to similar configurations, it offers higher power output, lower magnetic losses, and better thermal regulation. These findings support the advancement of reliable, energy-efficient BLDC motors for electric vehicles and industry, with future research focusing on advanced materials and manufacturing techniques for further optimization.

Keywords: BLDC motor, stator slot configuration, coil diameter, operational stability, motor performance, rotational speed.

References

1. Boloor Kashani, E., Halvaei Niasar, A. (2021). Reduction of torque ripple in an electrolytic capacitor-less BLDC motor drive by simultaneous speed and torque control method. *Ain Shams Engineering Journal, 12 (4),* 3703–3709. https://doi.org/10.1016/j.asej.2020.12.021
2. Rahmadani, A. A., Setiawan, B., Syaifudin, Y. W., Funabiki, N., Siradjuddin, I., Fatmawati, T. (2024). An Implementation of Early Warning System for Air Condition Using IoT and Instant Messaging. *Journal of Evrímata: Engineering and Physics, 2 (2),* 118–124. https://doi.org/10.70822/journalofevrmata.v2i02.61
3. Ammari, O., EL Majdoub, K., Giri, F., Baz, R. (2024). Modeling and control design for half electric vehicle with wheel BLDC actuator and Pacejka's tire. *Computers and Electrical Engineering, 116,* 109163. https://doi.org/10.1016/j.compeleceng.2024.109163
4. Johny, S., Kakkattil, S. S., Sunny, S., Sandeep, K. S., Sankar, V. (2021). Design and fabrication of foldable electric bicycle. *Materials Today: Proceedings, 46,* 9646–9651. https://doi.org/10.1016/j.matpr.2020.07.157
5. Anggraini, M. W., Luqman, M. (2024). Optimal USB to Serial Converter and Delphi Software Integration for Emergency Call Handling. *Journal of Evrímata: Engineering and Physics, 1 (2),* 47–60. https://doi.org/10.70822/journalofevrmata.vi.21
6. Sharma, S., Ali, I. (2024). Efficient energy management and cost optimization using multi-objective grey wolf optimization for EV charging/discharging in microgrid. *E-Prime – Advances in Electrical Engineering, Electronics and Energy, 10,* 100804. https://doi.org/10.1016/j.prime.2024.100804
7. Siradjuddin, I., Nurwicaksana, W. A., Riskitasari, S., Al Azhar, G., Hidayat, A. R., and Wicaksono, R. P. (2024). An Infrared Emitter Driver Circuit of SAT for MILES Application. *Journal of Evrímata: Engineering and Physics, 2 (2),* 129–137. https://doi.org/10.70822/journalofevrmata.v2i02.64
8. Andrade-Cedeno, R. J., Pinargote-Bravo, V. J., Amaya-Jaramillo, C. D., Palacios-López, L. A., Loor-Vera, A. T., Pérez-Rodríguez, J. A., Rodríguez-Borges, C. G. (2023). A sustainable and efficient alternative for water pumping in electrically isolated rural areas of Ecuador. *Energy Reports, 10,* 719–733. https://doi.org/10.1016/j.egyr.2023.07.027
9. Listiyono, L., Nurhadi, N., Md Yusof, H. (2023). Effect of brake padding strikes and reversing spring pressure on acceleration of drum brakes. *Journal of Evrímata: Engineering and Physics, 1 (2),* 38–41. https://doi.org/10.70822/journalofevrmata.vi.19
10. İnci, M., Büyük, M., Demir, M. H., İlbey, G. (2021). A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects. *Renewable and Sustainable Energy Reviews, 137,* 110648. https://doi.org/10.1016/j.rser.2020.110648
11. Syahyogi, A. E., Susilo, S. Hadi. (2024). Single propeller design of flying electric vehicles. *Evrimata: Journal of Mechanical Engineering, 1 (4),* 101–107. https://doi.org/10.70822/evrmata.v1i04.55
12. Magibalan, S., Ragu, C., Nithish, D., Raveeshankar, C., Sabarish, V. (2023). Design and fabrication of electric three-wheeled scooter for disabled persons. *Materials Today: Proceedings, 74,* 820–823. https://doi.org/10.1016/j.matpr.2022.11.179
13. Lazuardi, L., Akhlis Rizza, M., Maryono, M. (2024). Application Planning of Microhydro Electricity Generating Technology with 55 KW Power in the Mountains Using the River Flow of Coban Rondo Waterfall, Krajaan, Pandesari, Kec. Pujon, Malang, East Jawa. *Journal of Evrímata: Engineering and Physics, 1 (2),* 61–69. https://doi.org/10.70822/journalofevrmata.vi.25
14. Bayardo, R. G., Loukianov, A. G., Fuentes-Aguilar, R. Q., Utkin, V. I. (2020). Adaptive speed tracking controller for a brush-less DC motor using singular perturbation. *IFAC-PapersOnLine, 53 (2),* 3880–3885. https://doi.org/10.1016/j.ifacol.2020.12.2100
15. Saukani, I., Nuraini, E., Sukoco Heru Sumarno, A., Tri Turani Saptawati, R., Islahunufus, I., Sifaunnufus Ms, F. I. (2024). Buck-boost converter in photovoltaics for battery chargers. *Journal of Evrímata: Engineering and Physics, 2 (1),* 85–89. https://doi.org/10.70822/journalofevrmata.vi.26
16. Reynaldo, Winoko, Y. A. (2024). ESP 8266-Based Car Battery Current and Voltage Monitoring Design. *Evrimata: Journal of Mechanical Engineering, 1 (2),* 51–56. https://doi.org/10.70822/evrmata.vi.43
17. Hema, R., Venkatarangan, M. J. (2022). Adoption of EV: Landscape of EV and opportunities for India. *Measurement: Sensors, 24,* 100596. https://doi.org/10.1016/j.measen.2022.100596
18. Prayudha, A. T., Wahyudi, B. (2024). Simulation Strength Analysis on PVC Pipe Blade Propeller Horizontal Axis Wind Turbine with Tip Elbow. *Journal of Evrímata: Engineering and Physics, 23 (1),* 78–84. https://doi.org/10.70822/journalofevrmata.vi.31
19. Joy, J., Ushakumari, S. (2016). Performance Comparison of a Sensorless PMBLDC Motor Drive System with Conventional and Fuzzy Logic Controllers. *Procedia Technology, 25,* 643–651. https://doi.org/10.1016/j.protcy.2016.08.156
20. Al Kahvi, M. B., Susilo, S. H. (2024). Battery Management System (BMS) planning on quadcopter flying electric vehicle. *Journal of Evrímata: Engineering and Physics, 2 (2),* 112–117. https://doi.org/10.70822/journalofevrmata.v2i02.46
21. Varshney, A., Gupta, D., Dwivedi, B. (2017). Speed response of brushless DC motor using fuzzy PID controller under varying load condition. *Journal of Electrical Systems and Information Technology, 4 (2),* 310–321. https://doi.org/10.1016/j.jesit.2016.12.014
22. Hadi Susilo, S., Kurniawan, K., Yudiyanto, E., Indra Kurniawan, B. (2024). Simulation of Quadcopter Flying Electric Vehicle Chassis. *Evrimata: Journal of Mechanical Engineering, 1 (3),* 77–80. https://doi.org/10.70822/evrmata.v1i03.48
23. Huda, A. N., Pebrianti, D., Binti MD. Zain, Z. (2023). Integrated Robotic Arm Control: Inverse Kinematics, Trajectory Planning, and Performance Evaluation for Automated Welding. *Asian Journal Science and Engineering, 2 (2),* 82. https://doi.org/10.51278/ajse.v2i2.1021
24. Widjanarko, Alia, N., Perdana, F. A., Udianto, P., Puspitasari, E. (2024). Sustainable Power Generation through Dual-Axis Solar Tracking for Off Grid 100Wp Photovoltaic Systems. *Evrimata: Journal of Mechanical Engineering, 1 (4),* 118–124. https://doi.org/10.70822/evrmata.v1i04.63
25. Preethiraj, P. M., Belwin Edward, J. (2024). Design of novel DC-DC interleaved boost converter for BLDC application. *Heliyon, 10 (22),* e40041. https://doi.org/10.1016/j.heliyon.2024.e40041

ISSN-L 2664-9969; E-ISSN 2706-5448

DOI: 10.15587/2706-5448.2025.323745

DETERMINATION OF THE INFLUENCE OF THE NUMBER OF PROFILE HOLES ON THE EFFICIENCY INDICATORS OF HEMP SEED DEHULLER IMPELLERS

pages 21–28

Viktor Sheichenko, *Doctor of Technical Sciences, Professor, Department of Agricultural Engineering and Road Transport, Poltava State Agrarian University, Poltava, Ukraine, e-mail: vsheychenko@ukr.net, ORCID: https://orcid.org/0000-0003-2751-6181*

Dmytro Petrachenko, *PhD, Department of Agroengineering, Separate Structural Subdivision "Hlukhiv Agrotechnical Professional College of Sumy National Agrarian University", Glukhiv, Ukraine, ORCID: https://orcid.org/0000-0002-1347-9562*

Anatolii Lytvynenko, *PhD, Director, Separate Structural Subdivision "Hlukhiv Agrotechnical Professional College of Sumy National Agrarian University", Glukhiv, Ukraine, ORCID: https://orcid.org/0009-0002-1707-8798*

Oleksandra Bilovod, *PhD, Associate Professor, Department of Mechanical and Electrical Engineering, Poltava State Agrarian University, Poltava, Ukraine, ORCID: https://orcid.org/0000-0003-3470-0091*

Denys Sheichenko, *Department of Agricultural Engineering, Poltava State Agrarian University, Poltava, Ukraine, ORCID: https://orcid.org/0009-0002-0427-479X*

Yurii Brodovych, *PhD, Department of Engineering, Technology and Professional Education, Mukachevo State University, Mukachevo, Ukraine, ORCID: https://orcid.org/0009-0005-6458-3553*

Vitaliy Shevchuk, *PhD, Senior Researcher, Department of Agricultural Engineering, Uman National University of Horticulture, Uman, Ukraine, ORCID: https://orcid.org/0000-0001-8305-4714*

Misha Shevchuk, *PhD, Department of Agricultural Engineering, Uman National University of Horticulture, Uman, Ukraine, ORCID: https://orcid.org/0000-0002-0123-0348*

The object of the research is technological processes, seeds and kernels of industrial hemp, centrifugal dehullers, dehuller impellers.

The research is aimed at increasing the efficiency of centrifugal dehulling of industrial hemp seeds by determining the influence of the number of profile holes in the impellers.

Two variants of the impeller design were developed and tested: with four and six profile holes. The research was conducted on seeds of the "Glesia" variety under stable processing conditions, including optimal humidity (8.4 %) and standardized wheel rotation parameters (6000±200 rpm).

According to the research results, it was established:

– an impeller with four profile holes in five dehulling cycles enabled a total kernel yield of 34.81 %. Under such conditions, the bulk of the seeds were dehulled in the first three cycles;

– the impeller with six profile holes made it possible to ensure a total kernel yield of 34.48 % in three dehulling cycles. Under these conditions, a significant part of the kernels was separated in the first two cycles.

According to the results of the analysis of the dehulling indicators, it was noted:

– in the first two cycles, the wheel with six holes separated up to 29.71 % of the kernels, and the wheel with four holes – up to 22.02 %;

– the use of the design of the wheel with six holes reduced the remains of undehulled seeds after the third cycle to 4.24 % of the initial mass, while the wheel with four holes – up to 16.23 %.

The advantages of the centrifugal dehulling method, which is based on the principle of converting kinetic energy into impact, were noted. This made it possible to separate the shells from the kernels without prior calibration of industrial hemp seeds.

The research results demonstrated the advantages of the improved design, which includes an impeller with six profile holes, and the prospects of its use to increase the productivity of industrial hemp seed dehulling.

Keywords: hemp seeds, seed kernels, centrifugal dehulling, impeller, impeller profile holes, dehulling efficiency.

References

1. Farinon, B., Molinari, R., Costantini, L., Merendino, N. (2020). The Seed of Industrial Hemp (*Cannabis sativa L.*): Nutritional Quality and Potential Functionality for Human Health and Nutrition. *Nutrients, 12 (7),* 1935. https://doi.org/10.3390/nu12071935
2. Alonso-Esteban, J. I., Pinela, J., Ćirić, A., Calhelha, R. C., Soković, M., Ferreira, I. C. F. R. et al. (2022). Chemical composition and biological activities of whole and dehulled hemp (*Cannabis sativa L.*) seeds. *Food Chemistry, 374,* 131754. https://doi.org/10.1016/j.foodchem.2021.131754
3. Oseyko, M., Sova, N., Yefimov, V., Petrachenko, D. (2024). Chemical composition of seeds of industrial Ukrainian hemp varieties. *Ukrainian Food Journal, 13 (3),* 542–556. https://doi.org/10.24263/2304-974x-2024-13-3-8
4. Sheichenko, V., Petrachenko, D. (2024). Dehulling of Industrial Hemp Seeds with High-Performance Mechanisms. National Interagency Scientific and Technical Collection of Works. *Design, Production and Exploitation of Agricultural Machines, 54,* 55–62. https://doi.org/10.32515/2414-3820.2024.54.55-62
5. Montero, L., Ballesteros-Vivas, D., Gonzalez-Barrios, A. F., Sánchez-Camargo, A. del P. (2023). Hemp seeds: Nutritional value, associated bioactivities and the potential food applications in the Colombian context. *Frontiers in Nutrition, 9.* https://doi.org/10.3389/fnut.2022.1039180
6. Kabir, A., Fedele, O. (2018). A Review of Shelling, Threshing, De-Hulling and Decorticating Machines. *Open Access Journal of Agricultural Research, 3 (1).* https://doi.org/10.23880/oajar-16000148
7. Baker, B. (2015). *Dehulling ancient grains: economic considerations and equipment.* Available at: https://eorganic.org/node/13028 Last accessed: 08.01.2025
8. Manjeet, P., Pragi, S., Kanak, D., Anil, B. (2017). Pod Shelling Machines-A Review. *International Journal of Agricultural Science and Research (IJASR), 7,* 321–326.
9. Sharma, V., Pradhan, R. C., Naik, S. N., Bhatnagar, N., Singh, S. (2013). Evaluation of a centrifugal impaction-type decorticator for shelling tung fruits. *Industrial Crops and Products, 43,* 126–131. https://doi.org/10.1016/j.indcrop.2012.06.046
10. *Complex Oilseed Processing.* Available at: https://www.farmet.cz/en/complex-oilseed-processing
11. Li, A., Jia, F., Chu, Y., Han, Y., Li, H., Sun, Z. et al. (2023). Simulation of the movement of rice grains in a centrifugal huller by discrete element method and the influence of blade shape. *Biosystems Engineering, 236,* 54–70. https://doi.org/10.1016/j.biosystemseng.2023.10.013
12. Bernik, R., Stajnko, D., Demšar, I. (2020). Comparison of the Kernel Quality of Different Walnuts (*Juglans regia L.*) Varieties Shelled with Modified Centrifugal Sheller. *Erwerbs-Obstbau, 62 (2),* 213–220. https://doi.org/10.1007/s10341-020-00473-2
13. Sheichenko, V., Petrachenko, D., Koropchenko, S., Rogovskii, I., Gorbenko, O., Volianskyi, M., Sheichenko, D. (2024). Substantiating the rational parameters and operation modes for the hemp seed centrifugal dehuller. *Eastern-European Journal of Enterprise Technologies, 2 (1 (128)),* 34–48. https://doi.org/10.15587/1729-4061.2024.300174
14. Lachuga, Yu. F., Ibyatov, R. I., Ziganshin, B. G., Shogenov, Yu. H., Dmitriev, A. V. (2020). Simulation of the Grain Trajectory along Working Bodies of the Pneumatic Mechanical Dehuller. *Russian Agricultural Sciences, 46 (5),* 534–538. https://doi.org/10.3103/s1068367420050110
15. Cao, B., Jia, F., Zeng, Y., Han, Y., Meng, X., Xiao, Y. (2018). Effects of rotation speed and rice sieve geometry on turbulent motion of particles in a vertical rice mill. *Powder Technology, 325,* 429–440. https://doi.org/10.1016/j.powtec.2017.11.048
16. Baker, A., Dwyer-Joyce, R., Briggs, C., Brockfeld, M. (2012). Effect of different rubber materials on husking dynamics of paddy rice. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 226 (6),* 516–528. https://doi.org/10.1177/1350650111435601

17. Khodabakhshian, R., Bayati, M. R. (2011). Investigation into the Effects of Impeller Vane Patterns and Pistachio Nut Size on Hulling Efficiency of Pistachio Nuts using A Centrifugal Huller. *Journal of Food Processing & Technology, 2 (3).* https://doi.org/10.4172/2157-7110.1000115
18. *Nasinnia silskohospodarskykh kultur. Metody vyznachennia yakosti* (2004). DSTU 4138-2002. Kyiv: Derzhspozhyvstandart Ukrainy.
19. Khailis, H. A., Konovaliuk, D. M. (1992). *Osnovy proektuvannia i doslidzhennia silskohospodarskykh mashyn.* Kyiv: NMK VO, 320.

METALLURGICAL TECHNOLOGY

DOI: 10.15587/2706-5448.2025.322458

IDENTIFICATION OF TEMPERATURE IN CUPOLA FURNACE BASED ON THE CONSTRUCTION OF THE "SLAG COMPOSITION – SLAG VISCOSITY" MODEL

pages 29–33

Denys Nikolaiev, *PhD Student, Department of Foundry, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-8324-1760, e-mail: nikolaev@entc.com.ua*

Vadym Selivorstov, *Doctor of Technical Sciences, Professor, Department of Foundry Production, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0002-1916-625X*

Yuriy Dotsenko, *PhD, Associate Professor, Department of Foundry Production, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, ORCID: https://orcid.org/0000-0002-7734-7884*

Oleksandr Dzevochko, *PhD, Associate Professor, Head of Department of Technological Systems Automation and Environmental Monitoring, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0002-1297-1045*

Alevtyna Pereverzieva, *Assistant, Department of Technological Systems Automation and Environmental Monitoring, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0003-2072-2521*

Alona Dzevochko, *PhD, Associate Professor, Department of Technological Systems Automation and Environmental Monitoring, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine, ORCID: https://orcid.org/0000-0001-5988-5577*

The object of the study in the work is the temperature regime of melting in a cupola.

The existing problem is that due to the aggressive high-temperature environment, continuous measurement of the parameters of the internal environment in the working space of the cupola furnace is too difficult. Even with the implementation of such a possibility, errors of the first and second types may occur. This necessitates indirect control of the temperature regime, which could provide a solution to the identification problem – whether the control system is really operating in normal mode and meets the accuracy requirements, or whether there is a parametric failure along the corresponding control circuit.

The existence of the specified problem requires solutions related to the definition of criteria for evaluating the temperature regime, by which it would be possible to verify the reliable functioning of the melting control system.

A criterion for evaluating the temperature regime of melting by the viscosity of the slag as a function of its composition is proposed, which allows identifying the temperature regime of melting with an accuracy of 96 %. This result is due to the proposed two-stage procedure, in which the first stage is the construction of mathematical models that describe the influence of the slag composition on the viscosity, and the second is the construction of a criterion based on the density distribution of the discriminant function for both temperature regimes. Using the obtained criterion also makes it possible to determine the areas of chemical compositions, by which the temperature regime can also be identified. The relationships between the variables for the identification procedure are presented in the form of a structural diagram. The proposed solutions will allow determining the quality of the functioning of the temperature control loop in the melting control system based on periodic control.

The presented study will be useful for machine-building enterprises that have foundries in their structure, where cast iron is smelted for the manufacture of castings.

Keywords: cupola melting, slag composition, temperature regime in the cupola furnace, slag viscosity, temperature control loop in the cupola furnace.

References

1. Demin, D. A. (2012). Synthesis of optimal temperature regulator of electroarc holding furnace bath. *Scientific Bulletin of National Mining University, 6,* 52–58.
2. Demin, D. A. (2014). Mathematical description typification in the problems of synthesis of optimal controller of foundry technological parameters. *Eastern-European Journal of Enterprise Technologies, 1 (4 (67)),* 43–56. https://doi.org/10.15587/1729-4061.2014.21203
3. Demin, D. A. (2014). Computer-integrated electric-arc melting process control system. *Eastern-European Journal of Enterprise Technologies, 2 (9 (68)),* 18–23. https://doi.org/10.15587/1729-4061.2014.23512
4. Demin, D. (2017). Synthesis of optimal control of technological processes based on a multialternative parametric description of the final state. *Eastern-European Journal of Enterprise Technologies, 3 (4 (87)),* 51–63. https://doi.org/10.15587/1729-4061.2017.105294
5. Demin, D. (2019). Development of «whole» evaluation algorithm of the control quality of "cupola – mixer" melting duplex process. *Technology Audit and Production Reserves, 3 (1 (47)),* 4–24. https://doi.org/10.15587/2312-8372.2019.174449
6. Demin, D. (2023). Experimental and industrial method of synthesis of optimal control of the temperature region of cupola melting. *EUREKA: Physics and Engineering, 2,* 68–82. https://doi.org/10.21303/2461-4262.2023.002804
7. Jopkiewicz, A., Podrzucki, C. (2007). Tendencies to the Improvement of the Cupola Process. *Archives of foundry engineering, 13 (3),* 61–70.
8. Powell, W. L., Druschitz, A. P., Frost, J. (2008). Cupola Furnaces. *Casting,* 99–107. https://doi.org/10.31399/asm.hb.v15.a0005197
9. Aristizábal, R. E., Pérez, P. A., Katz, S., Bauer, M. E. (2014). Studies of a Quenched Cupola. *International Journal of Metalcasting, 8 (3),* 13–22. https://doi.org/10.1007/bf03355586
10. Ajah, S. A., Idorenyin, D., Nwokenkwo, U. C., Nwigwe, U. S., Ezurike, B. O. (2021). Thermal Analysis of a Conventional Cupola Furnace with Effects of Excess Air on the Flue Gases Specific Heat. *Journal of Materials and Environmental Science, 12 (2),* 192–204.
11. Demin, D., Domin, O. (2021). Adaptive technology for constructing the kinetic equations of reduction reactions under conditions of a priori uncertainty. *EUREKA: Physics and Engineering, 4,* 14–29. https://doi.org/10.21303/2461-4262.2021.001959
12. Demin, D. (2013). Adaptive modeling in problems of optimal control search termovremennoy cast iron. *Eastern-European Journal of Enterprise Technologies, 6 (4 (66)),* 31–37. https://doi.org/10.15587/1729-4061.2013.19453
13. Luis, C. J., Álvarez, L., Ugalde, M. J., Puertas, I. (2002). A technical note cupola efficiency improvement by increasing air blast temperature. *Journal of Materials Processing Technology, 120 (1-3),* 281–289. https://doi.org/10.1016/s0924-0136(01)01053-6
14. Jezierski, J., Janerka, K. (2011). Selected Aspects of Metallurgical and Foundry Furnace Dust Utilization. *Polish Journal of Environmental Studies, 20 (1),* 101–105.
15. Isnugroho, K., Birawidha, D. C. (2018). The production of pig iron from crushing plant waste using hot blast cupola. *Alexandria Engineering Journal, 57 (1),* 427–433. https://doi.org/10.1016/j.aej.2016.11.004

ISSN-L 2664-9969; E-ISSN 2706-5448

16. Larsen, E. D., Clark, D. E., Moore, K. L., King, P. E. (1997). *Intelligent control of Cupola Melting.* Available at: https://pdfs.semanticscholar.org/56c2/96af1d56d5cd963a5bcc38635142e5fa1968.pdf
17. Moore, K. L., Abdelrahman, M. A., Larsen, E., Clark, D., King, P. (1998). Experimental control of a cupola furnace. *Proceedings of the 1998 American Control Conference. ACC (IEEE Cat. No.98CH36207),* 3816–3821. https://doi.org/10.1109/acc.1998.703360
18. Nikolaiev, D. (2024). Construction of a cupola information profile for further modeling for the purpose of controlling melting processes. *ScienceRise*, 2, 3–14. http://doi.org/10.21303/2313-8416.2024.003674
19. Demin, D., Frolova, L. (2024). Construction of a logical-probabilistic model of casting quality formation for managing technological operations in foundry production. *EUREKA: Physics and Engineering, 6,* 104–118. https://doi.org/10.21303/2461-4262.2024.003518
20. Demin, D. (2020). Constructing the parametric failure function of the temperature control system of induction crucible furnaces. *EUREKA: Physics and Engineering, 6,* 19–32. https://doi.org/10.21303/2461-4262.2020.001489
21. Stanovska, I., Duhanets, V., Prokopovych, L., Yakhin, S. (2021). Classification rule for determining the temperature regime of induction gray cast iron. *EUREKA: Physics and Engineering, 1,* 60–66. https://doi.org/10.21303/2461-4262.2021.001604
22. Penziev, P., Lavryk, Y. (2023). Diagnostics of the temperature condition of cast iron melting in induction furnaces by the content of SiO_2 and CaO in slag. *ScienceRise, 1,* 14–20. https://doi.org/10.21303/2313-8416.2024.003558

MATERIALS SCIENCE

DOI: 10.15587/2706-5448.2025.322887

DETERMINATION OF THE INFLUENCE OF THE THERMOSTABILIZER CONTENT ON THE CYCLIC PROCESSING OF POLYVINYL CHLORIDE

pages 34–40

Andrii Savchuk, *PhD Student, Department of Chemical Technologies and Resource Saving, Kyiv National University of Technologies and Design, Kyiv, Ukraine, e-mail: Andriy.pvh@gmail.com, ORCID: https://orcid.org/0009-0008-6208-0399*

Taras Fedoriv, *PhD Student, Department of Chemical Technologies and Resource Saving, Kyiv National University of Technologies and Design, Kyiv, Ukraine, ORCID: https://orcid.org/0009-0002-4644-3993*

The object of the study is the process of cyclic recycling of polyvinyl chloride (PVC). The main problem of multiple recycling of polyvinyl chloride is poor thermal stability. This problem is associated with insufficient stabilization of polyvinyl chloride at the stage of manufacturing the initial product. Usually, such products are difficult to recycle, since the content of additives in polyvinyl chloride is designed for one-time manufacturing of products and does not provide for repeated cyclic recycling. In addition, it may be necessary to modify the PVC composition to obtain the characteristics necessary for a new application. The thermal stability of polyvinyl chloride can be improved by various methods of physical modification. One of the key methods is the introduction of a stabilizer in a rational amount. To solve the problems set in the work, PVC composites with an adjustable stabilizer content from 2 to 5 mass parts were manufactured. The manufactured composites were recycled up to 5 times. At each cycle of PVC composites processing, thermal stability and melting point were determined using the RM-200C Hapro rheometer plastograph (Harbin University of Science and Technology Harbin Technology Co. Ltd, China). Mechanical properties were also determined on a tensile machine according to ISO 527-2:2012, Charpy impact strength according to ISO 179 and ASTM D256, and melt flow index according to ISO 1133:199.

The study found that increasing the stabilizer content by only 1–2 parts by mass from its base concentration of 3 parts by mass increases the life of the PVC composite by 1.5–2 times. A stabilizer content of 4–5 parts by mass allows maintaining sufficiently stable physical and mechanical characteristics of the PVC composite during 5 processing cycles.

As a result of the research, a PVC formulation suitable for cyclic processing was proposed, which is achieved by introducing 4–5 mass parts of the stabilizer at the stage of primary PVC production. This allows maintaining the mechanical characteristics of the material, valuable for the final application during multiple processing compared to typical PVC composites used on the market for the production of window profiles.

Keywords: thermal degradation, rheometric analysis, plastogram, tensile strength, impact strength, melt flow index, extrusion.

References

1. Ait-Touchente, Z., Khellaf, M., Raffin, G., Lebaz, N., Elaissari, A. (2023). Recent advances in polyvinyl chloride (PVC) recycling. *Polymers for Advanced Technologies, 35 (1).* https://doi.org/10.1002/pat.6228
2. Mathews, G. (2024). *PVC: production, properties and uses.* CRC Press, 400. https://doi.org/10.1201/9781003575863
3. *PVC Chemical Resistance Guide. Polyvinyl Chloride (PVC)* (2020). IPEX: Oakville.
4. Brockmann, W., Geiß, P. L., Klingen, J., Schröder, K. B. (2009). *Adhesive Bonding: Materials, Applications and Technology.* Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA. https://doi.org/10.1002/9783527623921
5. Wypych, G. (2020). *PVC Degradation and Stabilization.* Toronto: ChemTec Publishing. https://doi.org/10.1016/C2019-0-00335-4
6. Wypych, G. (2020). *PVC Formulary.* Toronto: ChemTec Publishing. https://doi.org/10.1016/c2019-0-00367-6
7. Cousins, K. (2002). *Polymers in Building and Construction.* Shawbury: Rapra Technology LTD.
8. Edo, G. I., Ndudi, W., Ali, A. B. M., Yousif, E., Zainulabdeen, K., Onyibe, P. N. et al. (2024). Poly(vinyl chloride) (PVC): an updated review of its properties, polymerization, modification, recycling, and applications. *Journal of Materials Science, 59 (47),* 21605–21648. https://doi.org/10.1007/s10853-024-10471-4
9. Unar, I. N., Soomro, S. A., Aziz, S. (2010). Effect of Various Additives on the Physical Properties of Polyvinylchloride Resin. *Pakistan Journal of Analytical & Environmental Chemistry, 11 (2),* 44–50.
10. Ciacci, L., Passarini, F., Vassura, I. (2017). The European PVC cycle: In-use stock and flows. *Resources, Conservation and Recycling, 123,* 108–116. https://doi.org/10.1016/j.resconrec.2016.08.008
11. Arnold, J. C., Maund, B. (1999). The properties of recycled PVC bottle compounds. 2: Reprocessing stability. *Polymer Engineering & Science, 39 (7),* 1242–1250. Portico. https://doi.org/10.1002/pen.11511
12. Arnold, J. C., Maund, B. (1999). The properties of recycled PVC bottle compounds. 1: Mechanical performance. *Polymer Engineering & Science, 39 (7),* 1234–1241. https://doi.org/10.1002/pen.11510
13. Chantreux, M., Ricard, D., Asia, L., Rossignol, S., Wong-Wah-Chung, P. (2021). Additives as a major source of radiolytic organic byproducts of polyvinyl chloride (PVC). *Radiation Physics and Chemistry, 188,* 109671. https://doi.org/10.1016/j.radphyschem.2021.109671

DOI: 10.15587/2706-5448.2025.323845

SETTING THE PARAMETERS OF THERMAL DESTRUCTION OF FIRE-RESISTANT WOOD

pages 41–47

Yuriy Tsapko, *Doctor of Technical Sciences, Professor, Department of Building Materials, Kyiv National University of Construction and Architecture, Kyiv, Ukraine, e-mail: juriyts@ukr.net, ORCID: https://orcid.org/0000-0003-0625-0783*

Kateryna Pushkarova, *Doctor of Technical Sciences, Professor, Department of Building Materials, Kyiv National University of Construction and Architecture, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0001-7640-8625*

Aleksii Tsapko, *PhD, Senior Researcher, Department of Building Materials, Kyiv National University of Construction and Architecture, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0003-2298-068X*

Oksana Berdnyk, *PhD, Associate Professor, Department of Technology of Building Structures and Products, Kyiv National University of Construction and Architecture, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0001-5321-3518*

Olga Bondarenko, *PhD, Associate Professor, Department of Building Materials, Kyiv National University of Construction and Architecture, Kyiv, Ukraine, ORCID: https://orcid.org/0000-0002-8164-6473*

The problem of using wood is to ensure resistance to high-temperature flame and application technology. Therefore, the object of research was to change the parameters of thermal destruction of wood during fire protection by impregnation and intumescent coating. It has been proven that for wood treated by impregnation, the destruction processes slow down, so the mass loss is reduced by 3–5 times, the process increases in the region of higher temperatures with a significant coke residue. As for wood treated with intumescent coating, in the temperature range of 200–300 °C, pentaerythritol begins to decompose with the formation of aldehydes and a foam coke center is formed. The beginning of intensive mass loss coincides with the temperature of 320–330 °C, on which the sublimation peak of melamine is superimposed, starting at a temperature of 330 °C, which ends at a temperature of more than 420 °C. The obtained activation energy of wood is 30.03 kJ/mol, treatment of wood with impregnating agents increases the activation energy during its thermal decomposition by more than two times, and treatment with an intumescent coating by more than 4.4 times. After pyrolysis of wood treated with flame retardants, the mixtures of destruction products differ significantly in the content of carbon dioxide, nitrogen and the amount of combustible gases. Thus, for wood treated with the composition DSA-1, the amount of nitrogen increased by more than 46 times, and the amount of combustible gases decreased by more than 3 times. An even greater difference was recorded during treatment of wood with an intumescent coating. In particular, it was found that the amount of combustible gases decreased by more than 4 times, and the amount of nitrogen increased by more than 56 times. The practical significance lies in the fact that the results obtained were taken into account when developing a reactive coating. Thus, there are grounds to argue about the possibility of directed regulation of the wood protection process through the use of coatings capable of forming a protective layer on the surface.

Keywords: protective agents, fire resistance, volatile products, mass loss, surface treatment, protection efficiency.

References

1. Chernukha, A., Chernukha, A., Kovalov, P., Savchenko, A. (2021). Thermodynamic Study of Fire-Protective Material. *Materials Science Forum, 1038,* 486–491. https://doi.org/10.4028/www.scientific.net/msf.1038.486
2. Lee, Y. X., Wang, W., Lei, Y., Xu, L., Agarwal, V., Wang, C., Yeoh, G. H. (2025). Flame-retardant coatings for wooden structures. *Progress in Organic Coatings, 198,* 108903. https://doi.org/10.1016/j.porgcoat.2024.108903
3. Kochubei, V., Mykhalichko, B., Lavrenyuk, H. (2021). Elaboration, thermogravimetric analysis, and fire testing of a new type of wood-sawdust composite materials based on epoxy–amine polymers modified with copper(II) hexafluorosilicate. *Fire and Materials, 46 (3),* 587–594. https://doi.org/10.1002/fam.3008
4. Xiao, X., Xiao, X., Liu, S., Li, Y., Li, Y., Li, M. (2024). Green and efficient flame-retardant nanocomposites from hydroxyapatite nanosheets modified porous wood. *Industrial Crops and Products, 219,* 119105. https://doi.org/10.1016/j.indcrop.2024.119105
5. Koparipek-Arslan, N., Kaynak-Uraz, E., Senses, E. (2024). Dynamically bonded cellulose nanocrystal hydrogels: Structure, rheology and fire prevention performance. *Carbohydrate Polymers, 334,* 122013. https://doi.org/10.1016/j.carbpol.2024.122013
6. Tuble, K. A. Q., Omisol, C. J. M., Abilay, G. Y., Tomon, T. R. B., Aguinid, B. J. M., Dumancas, G. G. et al. (2024). Synergistic effect of phytic acid and eggshell bio-fillers on the dual-phase fire-retardancy of intumescent coatings applied on cellulosic substrates. *Chemosphere, 358,* 142226. https://doi.org/10.1016/j.chemosphere.2024.142226
7. Rodriguez-Melendez, D., Vest, N. A., Kolibaba, T. J., Quan, Y., Zhang, Z., Iverson, E. T. et al. (2024). Boron-based polyelectrolyte complex nanocoating for fire protection of engineered wood. *Cellulose, 31 (5),* 3083–3094. https://doi.org/10.1007/s10570-024-05773-4
8. Wang, X., Wang, B., Sun, J., Yu, L., Yang, G., Guo, H. (2023). Flame-retardant composite derived from polyurethane/wood-fiber. *Fire and Materials, 48 (2),* 273–285. https://doi.org/10.1002/fam.3182
9. Kumar, S., Shukla, S. K. (2023). Synergistic evolution of flame-retardant hybrid structure of poly vinyl alcohol, starch and kaolin for coating on wooden substrate. *Journal of Polymer Research, 30 (2).* https://doi.org/10.1007/s10965-023-03463-6
10. Zhan, W., Ma, Z., Du, D., Sun, Z., Li, L., Gu, Z. et al. (2022). Effects of bagasse fiber as the renewable environmentally friendly material on the properties of the waterborne intumescent fireproof coating. *Journal of Applied Polymer Science, 139 (34).* https://doi.org/10.1002/app.52815
11. Mihăilă, A., Danu, M., Ibănescu, C., Anghel, I., Şofran, I.-E., Balanescu, L. V. et al. (2021). Thermal characterization and rheological behavior of some varnishes and paints used for wood protection. *International Journal of Environmental Science and Technology, 19 (7),* 6299–6314. https://doi.org/10.1007/s13762-021-03579-6
12. Khadiran, T., Jasmani, L., Rusli, R. (2022). Application of Nanomaterials for Wood Protection. *Emerging Nanomaterials,* 179–196. https://doi.org/10.1007/978-3-031-17378-3_7
13. Broido, A. (1969). A simple, sensitive graphical method of treating thermogravimetric analysis data. *Journal of Polymer Science Part A-2: Polymer Physics, 7 (10),* 1761–1773. https://doi.org/10.1002/pol.1969.160071012
14. Tsapko, Y., Tsapko, A. (2017). Establishment of the mechanism and fireproof efficiency of wood treated with an impregnating solution and coatings. *Eastern-European Journal of Enterprise Technologies, 3 (10 (87)),* 50–55. https://doi.org/10.15587/1729-4061.2017.102393
15. Shestak, Ia. (1987). *Teoriia termicheskogo analiza.* Mir, 1987. 455.
16. Tsapko, J., Tsapko, A. (2017). Simulation of the phase transformation front advancement during the swelling of fire retardant coatings. *Eastern-European Journal of Enterprise Technologies, 2 (11 (86)),* 50–55. https://doi.org/10.15587/1729-4061.2017.73542
17. Tsapko, Y., Tsapko, A., Likhnyovskyi, R., Sukhanevych, M., Zapolskiy, L., Illiuchenko, P., Bedratiuk, O. (2024). Establishing patterns in reducing fire-dangerous properties of sip panels fire-protected with reactive coating. *Eastern-European Journal of Enterprise Technologies, 1 (10 (127)),* 47–54. https://doi.org/10.15587/1729-4061.2024.298266
18. Tsapko, Y., Likhnyovskyi, R., Tsapko, A., Bielikova, K., Poteriaiko, S., Illiuchenko, P., Bondarenko, O. (2023). Determining patterns in the formation of an insulation layer of foam coke when protecting concrete against fire by reactive coating. *Eastern-European Journal of Enterprise Technologies, 6 (10 (126)),* 65–72. https://doi.org/10.15587/1729-4061.2023.293685
19. Kochubei, V., Kozyar, N., Lavrenyuk, H., Mykhalichko, B. (2024). Metal-Coordinated Epoxy-Amine Composition with Reduced Fire Risk: Elaboration, Thermal and Ignition Resistance. *Periodica Polytechnica Chemical Engineering, 68 (3),* 446–453. https://doi.org/10.3311/ppch.36543
20. Mykhalichko, B., Lavrenyuk, H. (2022). Flame Protection Technologies for Wood: Developing and Testing for Fire of Timbers with a Flame-retardant Coating Based on the Epoxy-amine Composite Modified by Copper(II) Hexafluorosilicate. *Periodica Polytechnica Chemical Engineering, 66 (2),* 304–312. https://doi.org/10.3311/ppch.19050

DOI: 10.15587/2706-5448.2025.323965

DETERMINATION OF THE DEPENDENCE OF ETTRINGITE PHASE STABILITY IN NANOMODIFIED CEMENT SYSTEMS UNDER THE INFLUENCE OF VARIOUS FACTORS

pages 48–57

Hanna Hryshko, *PhD, Associate Professor, Department of Technology of Building Materials, Products and Structures, Ukrainian State University of Science and Technologies, Educational and Scientific Institute "Prydniprovska State Academy of Civil Engineering and Architecture", Dnipro, Ukraine, ORCID: https://orcid.org/0009-0002-3872-6555, e-mail: hryshko.hanna@pdaba.edu.ua*

ISSN-L 2664-9969; E-ISSN 2706-5448

The object of research is the stabilization of the ettringite phase in cement systems containing gypsum-alumina cement and nanoparticles. One of the most problematic areas is the instability of the ettringite phase, which affects the durability and mechanical characteristics of materials. The main problems are insufficient consideration of transitions between macro-, micro- and nanolevels when forming the structure of the hardening system. Multicomponent mixtures cannot be calculated using existing models, since a significant number of initial parameters and characteristics are not taken into account. The transition of systems from one level to another is not taken into account, namely the transition of systems from macro- to micro- and to nanolevel. The study used nanomodification of cement systems based on gypsum-alumina cement by introducing synthesized composites (carbon nanoparticles) into the hardening matrix. The influence of the raw material mixture components on the correction of the factors of instability of the ettringite phase, the processes of structure formation was studied, which allows in the future to eliminate these shortcomings and control the structure formation at different levels of the hardening matrix system. The optimal amount of calcium sulfate for the formation of ettringite was obtained – 30–40 % of the composition mass. This is due to the fact that the proposed composition of GC-40/G – 70/30 % has a significant amount of calcium hydroaluminates in the hydration process, the compressive and bending strengths are, respectively, 14 and 10 MPa. In particular, a dispersed medium resistant to delamination is formed, the water release of which is stabilized within 3 hours. Obtaining such values is ensured due to the fact that ettringite is formed in the early stages of hardening and provides an increase in the strength of the stone at a high speed. Compared with similar known gypsum-alumina cements, this provides advantages in the formation of high-basic ettringite. The results obtained are recommended for use in the construction of tunnels, restoration of hydraulic structures and transport infrastructure.

Keywords: binder, solution, ettringite, ettringite stabilization, aluminate cements, sulfoaluminate cements.

References

1. Gołaszewski, J., Gołaszewska, M. (2021). Properties of mortars with Calcium Sulfoaluminate cements with the addition of Portland cement and limestone. *Archives of Civil Engineering, 67 (2),* 425–435. https://doi.org/10.24425/ace.2021.137177
2. Yanze, G. A. N., Nana, A., Lemougna, P. N., Kaze, R. C., Tome, S., Rahier, H. et al. (2024). Development of calcium sulfoaluminate cements from rich-alumina bauxite and marble wastes: Physicochemical and microstructural characterization. *International Journal of Ceramic Engineering & Science, 6 (3).* https://doi.org/10.1002/ces2.10216
3. Godinho, J. P., De Souza Júnior, T. F., Medeiros, M. H. F., Silva, M. S. A. (2020). Factors influencing ultrasonic pulse velocity in concrete. *Revista IBRACON de Estruturas e Materiais, 13 (2),* 222–247. https://doi.org/10.1590/s1983-41952020000200004
4. Matschei, T., Lothenbach, B., Glasser, F. P. (2007). The AFm phase in Portland cement. *Cement and Concrete Research, 37 (2),* 118–130. https://doi.org/10.1016/j.cemconres.2006.10.010
5. Zhang, Y., Chang, J., Ji, J. (2018). AH3 phase in the hydration product system of AFt-AFm-AH3 in calcium sulfoaluminate cements: A microstructural study. *Construction and Building Materials, 167,* 587–596. https://doi.org/10.1016/j.conbuildmat.2018.02.052
6. Wu, J., Liu, L., Deng, Y., Zhang, G., Zhou, A., Xiao, H. (2022). Use of recycled gypsum in the cement-based stabilization of very soft clays and its micro-mechanism. *Journal of Rock Mechanics and Geotechnical Engineering, 14 (3),* 909–921. https://doi.org/10.1016/j.jrmge.2021.10.002
7. Tuinukuafe, A., Noor, L., Ideker, J. H., Isgor, O. B. (2022). Factors Influencing the Electrical Properties of Ettringite Binders as Repair Materials. *MATEC Web of Conferences, 364,* 02005. https://doi.org/10.1051/matecconf/202236402005
8. Nguyen, H., Kunther, W., Gijbels, K., Samyn, P., Carvelli, V., Illikainen, M., Kinnunen, P. (2021). On the retardation mechanisms of citric acid in ettringite-based binders. *Cement and Concrete Research, 140,* 106315. https://doi.org/10.1016/j.cemconres.2020.106315
9. Cao, W., Zhu, H. (2024). A Study on the Application Performance of High-Aspect-Ratio Nano-Ettringite in Photocurable Resin Composites. *Materials, 17 (14),* 3492. https://doi.org/10.3390/ma17143492
10. Fang, Z., Zhang, S., Qi, W., Fan, Y., Shah, S. P., Zheng, J. (2024). Study on the Binding Behavior of Chloride Ion and Ettringite in Nano-Metakaolin Cement by Seawater Mixing and Curing Temperatures. *Materials, 17 (16),* 3943. https://doi.org/10.3390/ma17163943
11. Gołaszewska, M., Klemczak, B., Gołaszewski, J. (2021). Thermal Properties of Calcium Sulphoaluminate Cement as an Alternative to Ordinary Portland Cement. *Materials, 14 (22),* 7011. https://doi.org/10.3390/ma14227011
12. Zhang, G., Zhang, B., Hao, Y., Pang, Q., Tian, L., Ding, R., Ma, L., Wang, H. (2024). Effects of Lime Powder on the Properties of Portland Cement–Sulphoaluminate Cement Composite System at Low Temperature. *Materials, 17 (15),* 3658. https://doi.org/10.3390/ma17153658
13. Jacques, K. T. J., Zengyao, W., Shoude, W., Shifeng, H., Xin, C. (2023). The influence of different fine aggregate and cooling regimes on the engineering properties of sulphoaluminate cement mortar after heating. *Case Studies in Construction Materials, 18,* e01866. https://doi.org/10.1016/j.cscm.2023.e01866
14. Derevianko, V., Hryshko, A., Dubov, T. (2019). Etringite phase stabilization. *Building Materials and Products, 1-2 (103),* 18–25. https://doi.org/10.48076/2413-9890.2023-103-04
15. *EN 197-1:2011 – Cement – Part 1: Composition, specifications and conformity criteria for common cements.* Available at: https://standards.iteh.ai/catalog/standards/cen/64d327b1-d5ac-45e3-8b04-fafec9e0698e/en-197-1-2011?srsltid=AfmBOoqv2RY7WzBOfeH7aNVKxNM8xyXmYwWuFQTpSbLrU3_cxEfXCpTs
16. Derevianko, V. M., Hryshko, H. M., Dubov, T. M. (2024). Forming hydrate compounds system $3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$ during the aluminate cement minerals hydration. *Ukrainian Journal of Civil Engineering and Architecture, 5 (23),* 66–76. https://doi.org/10.30838/ujcea.2312.301024.66.1094.1
17. Derevianko, V. M., Kondratieva, N. V., Hryshko, H. M.; Kobets, A. S. (Ed.) (2023). Nanomodyfikovani zviazuvalni rechovyny dlia rozchyniv zakhystu ioniv. *Teoretychni ta praktychni pytannia ahrarnoi nauky.* Dnipro, 276–292.
18. Hryshko, H., Derevianko, V., Vatazhyshyn, O., Dubov, T. (2024). Researching the influence of the CaO/Al_2O_3 ratio on ettringite formation and obtaining the structure of a cement paste with special properties. *E3S Web of Conferences, 534,* 01005. https://doi.org/10.1051/e3sconf/202453401005

ELECTRICAL ENGINEERING AND INDUSTRIAL ELECTRONICS

DOI: 10.15587/2706-5448.2025.323117

ASSESSING THE POTENTIAL OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING FOR THERMAL MANAGEMENT IN ELECTRONIC DEVICES

pages 58–74

Oleh Yatskiv, *PhD Student, Department of System Design, Ivan Franko National University of Lviv, Lviv, Ukraine, e-mail: olegyatskiv@gmail.com, ORCID: https://orcid.org/0009-0007-8279-3671*

Bohdan Koman, *Doctor of Sciences in Physics and Mathematics, Professor, Department of System Design, Ivan Franko National University of Lviv, Lviv, Ukraine, ORCID: https://orcid.org/0000-0002-5369-0020*

The object of this study is the potential of artificial intelligence (AI) and machine learning (ML) techniques for thermal management in electronic devices. One of the most problematic aspects identified is the challenge of ensuring performance, reliability, and energy efficiency across diverse systems, including semiconductors, data centers, and consumer electronics. In the course of the research, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was used to systematically analyze 150 studies. These studies employed various approaches, such as predictive modeling, optimization algorithms, and real-time control systems.

Our findings indicate that AI-driven thermal management can reduce energy consumption by up to 81.81 %, depending on the cooling method and optimization. Reinforcement learning-based HVAC control achieves

17.4 % energy savings, while ML-driven power management in manycore systems reduces energy use by 30 % and lowers peak chip temperatures by 17 °C. Neural network-based thermal forecasting achieves <1 % error, improving prediction accuracy. Additionally, LSTM models for thermal prognosis achieve a 3.45 % relative prediction error, outperforming traditional regression methods.

These results highlight the potential of AI in optimizing thermal behavior across data centers, smart buildings, and manycore chip architectures. Key limitations were also identified, including limited data availability, challenges in model interpretability, and integration with legacy systems. The study provides a roadmap for scalable AI-driven thermal management. Emerging trends such as physics-informed ML models and the integration of cooling technologies promise innovation. Compared to conventional methods, these advancements deliver clear benefits in sustainability and adaptability.

Keywords: artificial intelligence (AI), machine learning (ML), thermal management, semiconductor thermal dissipation, predictive modelling, energy-efficient computing.

References

1. Wang, Y., Gao, Q., Wang, G., Lu, P., Zhao, M., Bao, W. (2018). A review on research status and key technologies of battery thermal management and its enhanced safety. *International Journal of Energy Research, 42 (13),* 4008–4033. https://doi.org/10.1002/er.4158
2. Fan, S., Duan, F. (2020). A review of two-phase submerged boiling in thermal management of electronic cooling. *International Journal of Heat and Mass Transfer, 150,* 119324. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119324
3. Feng, C.-P., Chen, L.-B., Tian, G.-L., Wan, S.-S., Bai, L., Bao, R.-Y. et al. (2019). Multifunctional Thermal Management Materials with Excellent Heat Dissipation and Generation Capability for Future Electronics. *ACS Applied Materials & Interfaces, 11 (20),* 18739–18745. https://doi.org/10.1021/acsami.9b03885
4. Zhang, N. (2024). Diagnosis and Prevention of Overheating Failures in Mechanical Equipment Based on Numerical Analysis of Temperature and Thermal Stress Fields. *International Journal of Heat and Technology, 42 (2),* 466–474. https://doi.org/10.18280/ijht.420212
5. Hu, R., Liu, Y., Shin, S., Huang, S., Ren, X., Shu, W. et al. (2020). Emerging Materials and Strategies for Personal Thermal Management. *Advanced Energy Materials, 10 (17).* https://doi.org/10.1002/aenm.201903921
6. Khosla, R., Miranda, N. D., Trotter, P. A., Mazzone, A., Renaldi, R., McElroy, C. et al. (2020). Cooling for sustainable development. *Nature Sustainability, 4 (3),* 201–208. https://doi.org/10.1038/s41893-020-00627-w
7. Syu, J.-H., Lin, J. C.-W., Srivastava, G., Yu, K. (2023). A Comprehensive Survey on Artificial Intelligence Empowered Edge Computing on Consumer Electronics. *IEEE Transactions on Consumer Electronics, 69 (4),* 1023–1034. https://doi.org/10.1109/tce.2023.3318150
8. Nazir, K., Memon, S. A., Saurbayeva, A. (2024). A novel framework for developing a machine learning-based forecasting model using multi-stage sensitivity analysis to predict the energy consumption of PCM-integrated building. *Applied Energy, 376,* 124180. https://doi.org/10.1016/j.apenergy.2024.124180
9. Mathew, J., Krishnan, S. (2021). A Review on Transient Thermal Management of Electronic Devices. *Journal of Electronic Packaging, 144 (1).* https://doi.org/10.1115/1.4050002
10. He, Z., Yan, Y., Zhang, Z. (2021). Thermal management and temperature uniformity enhancement of electronic devices by micro heat sinks: A review. *Energy, 216,* 119223. https://doi.org/10.1016/j.energy.2020.119223
11. Kucova, T., Prauzek, M., Konecny, J., Andriukaitis, D., Zilys, M., Martinek, R. (2023). Thermoelectric energy harvesting for internet of things devices using machine learning: A review. *CAAI Transactions on Intelligence Technology, 8 (3),* 680–700. https://doi.org/10.1049/cit2.12259
12. Chuttar, A., Thyagarajan, A., Banerjee, D. (2021). Leveraging Machine Learning (Artificial Neural Networks) for Enhancing Performance and Reliability of Thermal Energy Storage Platforms Utilizing Phase Change Materials. *Journal of Energy Resources Technology, 144 (2).* https://doi.org/10.1115/1.4051048
13. Tang, X., Guo, Q., Li, M., Wei, C., Pan, Z., Wang, Y. (2021). Performance analysis on liquid-cooled battery thermal management for electric vehicles based on machine learning. *Journal of Power Sources, 494,* 229727. https://doi.org/10.1016/j.jpowsour.2021.229727
14. Putrada, A. G., Abdurohman, M., Perdana, D., Nuha, H. H. (2022). Machine Learning Methods in Smart Lighting Toward Achieving User Comfort: A Survey. *IEEE Access, 10,* 45137–45178. https://doi.org/10.1109/access.2022.3169765
15. Rane, N., Choudhary, S., Rane, J. (2023). Enhancing thermal comfort through leading-edge design, monitoring, and optimization technologies: A review. *Sustainable and Clean Buildings, 1 (1),* 123–146. https://doi.org/10.2139/ssrn.4642529
16. Panduman, Y. Y. F., Funabiki, N., Fajrianti, E. D., Fang, S., Sukaridhoto, S. (2024). A Survey of AI Techniques in IoT Applications with Use Case Investigations in the Smart Environmental Monitoring and Analytics in Real-Time IoT Platform. *Information, 15 (3),* 153. https://doi.org/10.3390/info15030153
17. Khan, S. A., Eze, C., Dong, K., Shahid, A. R., Patil, M. S., Ahmad, S. et al. (2022). Design of a new optimized U-shaped lightweight liquid-cooled battery thermal management system for electric vehicles: A machine learning approach. *International Communications in Heat and Mass Transfer, 136,* 106209. https://doi.org/10.1016/j.icheatmasstransfer.2022.106209
18. Zhou, Y., Zheng, S., Zhang, G. (2020). A review on cooling performance enhancement for phase change materials integrated systems – flexible design and smart control with machine learning applications. *Building and Environment, 174,* 106786. https://doi.org/10.1016/j.buildenv.2020.106786
19. Rabienataj Darzi, A. A., Mousavi, S. M., Razbin, M., Li, M. (2024). Utilizing neural networks and genetic algorithms in AI-assisted CFD for optimizing PCM-based thermal energy storage units with extended surfaces. *Thermal Science and Engineering Progress, 54,* 102795. https://doi.org/10.1016/j.tsep.2024.102795
20. Xin, X., Zhang, Z., Zhou, Y., Liu, Y., Wang, D., Nan, S. (2024). A comprehensive review of predictive control strategies in heating, ventilation, and air-conditioning (HVAC): Model-free VS model. *Journal of Building Engineering, 94,* 110013. https://doi.org/10.1016/j.jobe.2024.110013
21. Suryawanshi, H. A. (2024). *Predictions of thermal behavior of power electronics components with neural networks.* [PhD thesis; Technische Hochschule Ingolstadt].
22. Pei, Q., Chen, S., Zhang, Q., Zhu, X., Liu, F., Jia, Z. et al. (2022). CoolEdge: hotspot-relievable warm water cooling for energy-efficient edge datacenters. *Proceedings of the 27th ACM International Conference on Architectural Support for Programming Languages and Operating Systems*, 814–829. https://doi.org/10.1145/3503222.3507713
23. Antal, M., Cioara, T., Anghel, I., Gorzenski, R., Januszewski, R., Oleksiak, A. et al. (2019). Reuse of Data Center Waste Heat in Nearby Neighborhoods: A Neural Networks-Based Prediction Model. *Energies, 12 (5),* 814. https://doi.org/10.3390/en12050814
24. Sohel Murshed, S. M., Nieto de Castro, C. A. (2017). A critical review of traditional and emerging techniques and fluids for electronics cooling. *Renewable and Sustainable Energy Reviews, 78,* 821–833. https://doi.org/10.1016/j.rser.2017.04.112
25. Chakraborty, S., Shukla, D., Kumar Panigrahi, P. (2024). A review on coolant selection for thermal management of electronics and implementation of multiple-criteria decision-making approach. *Applied Thermal Engineering, 245,* 122807. https://doi.org/10.1016/j.applthermaleng.2024.122807
26. Schreiber, T., Netsch, C., Eschweiler, S., Wang, T., Storek, T., Baranski, M., Müller, D. (2021). Application of data-driven methods for energy system modelling demonstrated on an adaptive cooling supply system. *Energy, 230,* 120894. https://doi.org/10.1016/j.energy.2021.120894
27. Guo, C. Y., Muhieldeen, M. W., Teng, K. H., Ang, C. K., Lim, W. H. (2024). A novel thermal management system for lithium-ion battery modules combining indirect liquid-cooling with forced air-cooling: Deep learning approach. *Journal of Energy Storage, 94,* 112434. https://doi.org/10.1016/j.est.2024.112434
28. Pagani, S., Manoj, P. D. S., Jantsch, A., Henkel, J. (2020). Machine Learning for Power, Energy, and Thermal Management on Multicore Processors: A Survey. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 39 (1),* 101–116. https://doi.org/10.1109/tcad.2018.2878168
29. Ilager, S., Buyya, R. (2021). Energy and thermal-aware resource management of cloud data centres: A taxonomy and future directions. *arXiv preprint arXiv:2107.02342*

ISSN-L 2664-9969; E-ISSN 2706-5448

30. He, Z., Guo, W., Zhang, P. (2022). Performance prediction, optimal design and operational control of thermal energy storage using artificial intelligence methods. *Renewable and Sustainable Energy Reviews, 156,* 111977. https://doi.org/10.1016/j.rser.2021.111977

31. Chuttar, A., Banerjee, D. (2021). Machine Learning (ML) Based Thermal Management for Cooling of Electronics Chips by Utilizing Thermal Energy Storage (TES) in Packaging That Leverages Phase Change Materials (PCM). *Electronics, 10 (22),* 2785. https://doi.org/10.3390/electronics10222785

32. Amiraski, M., Werner, D., Hankin, A., Sebot, J., Vaidyanathan, K., Hempstead, M. (2023). Boreas: A Cost-Effective Mitigation Method for Advanced Hotspots using Machine Learning and Hardware Telemetry. *2023 IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS),* 295–305. https://doi.org/10.1109/ispass57527.2023.00036

33. Okulu, D., Selimefendigil, F., Öztop, H. F. (2022). Review on nanofluids and machine learning applications for thermoelectric energy conversion in renewable energy systems. *Engineering Analysis with Boundary Elements, 144,* 221–261. https://doi.org/10.1016/j.enganabound.2022.08.004

34. Blad, C., Bøgh, S., Kallesøe, C. S. (2022). Data-driven Offline Reinforcement Learning for HVAC-systems. *Energy, 261,* 125290. https://doi.org/10.1016/j.energy.2022.125290

35. Correa-Jullian, C., Cardemil, J. M., López Droguett, E., Behzad, M. (2020). Assessment of Deep Learning techniques for Prognosis of solar thermal systems. *Renewable Energy, 145,* 2178–2191. https://doi.org/10.1016/j.renene.2019.07.100

36. Patel, N., Krishnamurthy, P., Amrouch, H., Henkel, J., Shamouilian, M., Karri, R., Khorrami, F. (2022). Towards a New Thermal Monitoring Based Framework for Embedded CPS Device Security. *IEEE Transactions on Dependable and Secure Computing, 19 (1),* 524–536. https://doi.org/10.1109/tdsc.2020.2973959

37. Zhang, Q., Meng, Z., Hong, X., Zhan, Y., Liu, J., Dong, J. et al. (2021). A survey on data center cooling systems: Technology, power consumption modeling and control strategy optimization. *Journal of Systems Architecture, 119,* 102253. https://doi.org/10.1016/j.sysarc.2021.102253

38. Chen, W.-Y., Shi, X.-L., Zou, J., Chen, Z.-G. (2022). Thermoelectric coolers for on-chip thermal management: Materials, design, and optimization. *Materials Science and Engineering: R: Reports, 151,* 100700. https://doi.org/10.1016/j.mser.2022.100700

39. Habibi Khalaj, A., Halgamuge, S. K. (2017). A Review on efficient thermal management of air- and liquid-cooled data centers: From chip to the cooling system. *Applied Energy, 205,* 1165–1188. https://doi.org/10.1016/j.apenergy.2017.08.037

40. Hannan, M. A., Lipu, M. S. H., Ker, P. J., Begum, R. A., Agelidis, V. G., Blaabjerg, F. (2019). Power electronics contribution to renewable energy conversion addressing emission reduction: Applications, issues, and recommendations. *Applied Energy, 251*, 113404. https://doi.org/10.1016/j.apenergy.2019.113404

41. Alzoubi, Y. I., Mishra, A. (2024). Green artificial intelligence initiatives: Potentials and challenges. *Journal of Cleaner Production, 468,* 143090. https://doi.org/10.1016/j.jclepro.2024.143090

42. Yahia, H. S., Zeebaree, S. R. M., Sadeeq, M. A. M., Salim, N. O. M., Kak, S. F., AL-Zebari, A. et al. (2021). Comprehensive Survey for Cloud Computing Based Nature-Inspired Algorithms Optimization Scheduling. *Asian Journal of Research in Computer Science, 8 (2),* 1–16. https://doi.org/10.9734/ajrcos/2021/v8i230195

43. Benoit-Cattin, T., Velasco-Montero, D., Fernández-Berni, J. (2020). Impact of Thermal Throttling on Long-Term Visual Inference in a CPU-Based Edge Device. *Electronics, 9 (12),* 2106. https://doi.org/10.3390/electronics9122106

44. Dhameliya, N. (2022). Power Electronics Innovations: Improving Efficiency and Sustainability in Energy Systems. *Asia Pacific Journal of Energy and Environment, 9 (2),* 71–80. https://doi.org/10.18034/apjee.v9i2.752

45. Iranfar, A., Terraneo, F., Csordas, G., Zapater, M., Fornaciari, W., Atienza, D. (2020). Dynamic Thermal Management with Proactive Fan Speed Control Through Reinforcement Learning. *2020 Design, Automation & Test in Europe Conference & Exhibition (DATE),* 418–423. https://doi.org/10.23919/date48585.2020.9116510

46. Zhang, X., Wu, Z., Sun, Q., Gu, W., Zheng, S., Zhao, J. (2024). Application and progress of artificial intelligence technology in the field of distribution network voltage Control: A review. *Renewable and Sustainable Energy Reviews, 192,* 114282. https://doi.org/10.1016/j.rser.2024.114282

47. Devasenan, M., Madhavan, S. (2024). Thermal intelligence: exploring AI's role in optimizing thermal systems – a review. *Interactions, 245 (1).* https://doi.org/10.1007/s10751-024-02122-6

48. Zhuang, D., Gan, V. J. L., Duygu Tekler, Z., Chong, A., Tian, S., Shi, X. (2023). Data-driven predictive control for smart HVAC system in IoT-integrated buildings with time-series forecasting and reinforcement learning. *Applied Energy, 338,* 120936. https://doi.org/10.1016/j.apenergy.2023.120936

49. Shaban, W. M., Kabeel, A. E., El Hadi Attia, M., Talaat, F. M. (2024). Optimizing photovoltaic thermal solar systems efficiency through advanced artificial intelligence driven thermal management techniques. *Applied Thermal Engineering, 247,* 123029. https://doi.org/10.1016/j.applthermaleng.2024.123029

50. Jalasri, M., Panchal, S. M., Mahalingam, K., Venkatasubramanian, R., Hemalatha, R., Boopathi, S. (2024). AI-Powered Smart Energy Management for Optimizing Energy Efficiency in High-Performance Computing Systems. *Future of Digital Technology and AI in Social Sectors.* IGI Global, 329–366. https://doi.org/10.4018/979-8-3693-5533-6.ch012

51. Zhang, K., Guliani, A., Ogrenci-Memik, S., Memik, G., Yoshii, K., Sankaran, R., Beckman, P. (2018). Machine Learning-Based Temperature Prediction for Runtime Thermal Management Across System Components. *IEEE Transactions on Parallel and Distributed Systems, 29 (2),* 405–419. https://doi.org/10.1109/tpds.2017.2732951

52. Han, Z., Zhao, J., Leung, H., Ma, K. F., Wang, W. (2021). A Review of Deep Learning Models for Time Series Prediction. *IEEE Sensors Journal, 21 (6),* 7833–7848. https://doi.org/10.1109/jsen.2019.2923982

53. Krivoguz, D., Ioshpa, A., Chernyi, S., Zhilenkov, A., Kustov, A., Zinchenko, A. (2024). Enhancing long-term air temperature forecasting with deep learning architectures. *Journal of Robotics and Control, 5 (3),* 706–716.

54. Ghahramani, A., Galicia, P., Lehrer, D., Varghese, Z., Wang, Z., Pandit, Y. (2020). Artificial Intelligence for Efficient Thermal Comfort Systems: Requirements, Current Applications and Future Directions. *Frontiers in Built Environment, 6.* https://doi.org/10.3389/fbuil.2020.00049

55. Zou, F., Yen, G. G., Tang, L., Wang, C. (2021). A reinforcement learning approach for dynamic multi-objective optimization. *Information Sciences, 546,* 815–834. https://doi.org/10.1016/j.ins.2020.08.101

56. Du, Y., Zhou, Z., Yang, X., Yang, X., Wang, C., Liu, J., Yuan, J. (2023). Dynamic thermal environment management technologies for data center: A review. *Renewable and Sustainable Energy Reviews, 187,* 113761. https://doi.org/10.1016/j.rser.2023.113761

57. Arshad, R., Zahoor, S., Shah, M. A., Wahid, A., Yu, H. (2017). Green IoT: An Investigation on Energy Saving Practices for 2020 and Beyond. *IEEE Access, 5,* 15667–15681. https://doi.org/10.1109/access.2017.2686092

58. Halhoul Merabet, G., Essaaidi, M., Ben Haddou, M., Qolomany, B., Qadir, J., Anan, M. et al. (2021). Intelligent building control systems for thermal comfort and energy-efficiency: A systematic review of artificial intelligence-assisted techniques. *Renewable and Sustainable Energy Reviews, 144,* 110969. https://doi.org/10.1016/j.rser.2021.110969

59. Emara, R. A. M. O. (2024). *Artificial Intelligence Based Controller for a Temperature Control System.* [PhD thesis; Faculty of Engineering, The British University in Egypt].

60. Cox, S. J., Kim, D., Cho, H., Mago, P. (2019). Real time optimal control of district cooling system with thermal energy storage using neural networks. *Applied Energy, 238*, 466–480. https://doi.org/10.1016/j.apenergy.2019.01.093

61. Gill, S. S., Xu, M., Ottaviani, C., Patros, P., Bahsoon, R., Shaghaghi, A. et al. (2022). AI for next generation computing: Emerging trends and future directions. *Internet of Things, 19,* 100514. https://doi.org/10.1016/j.iot.2022.100514

62. Datta, S., Chakraborty, W., Radosavljevic, M. (2022). Toward attojoule switching energy in logic transistors. *Science, 378 (6621),* 733–740. https://doi.org/10.1126/science.ade7656

63. Bahru, R., Hamzah, A. A., Mohamed, M. A. (2020). Thermal management of wearable and implantable electronic healthcare devices: Perspective and measurement approach. *International Journal of Energy Research, 45 (2),* 1517–1534. https://doi.org/10.1002/er.6031

64. Mallick, S., Gayen, D. (2023). Thermal behaviour and thermal runaway propagation in lithium-ion battery systems – A critical review. *Journal of Energy Storage, 62,* 106894. https://doi.org/10.1016/j.est.2023.106894

65. Zhao, J., Feng, X., Tran, M.-K., Fowler, M., Ouyang, M., Burke, A. F. (2024). Battery safety: Fault diagnosis from laboratory to real world. *Journal of Power Sources, 598*, 234111. https://doi.org/10.1016/j.jpowsour.2024.234111

66. Hanafi, A., Moawed, M., Abdellatif, O. (2024). Advancing Sustainable Energy Management: A Comprehensive Review of Artificial Intelligence Techniques in Building. *Engineering Research Journal (Shoubra), 53 (2),* 26–46. https://doi.org/10.21608/erjsh.2023.226854.1196

67. Tong, X. C. (2010). Development and Application of Advanced Thermal Management Materials. *Advanced Materials for Thermal Management of Electronic Packaging,* 527–593. https://doi.org/10.1007/978-1-4419-7759-5_12

68. Van Quang, T., Doan, D. T., Yun, G. Y. (2024). Recent advances and effectiveness of machine learning models for fluid dynamics in the built environment. *International Journal of Modelling and Simulation,* 1–27. https://doi.org/10.1080/02286203.2024.2371682

69. Hu, G., Prasianakis, N., Churakov, S. V., Pfingsten, W. (2024). Performance analysis of data-driven and physics-informed machine learning methods for thermal-hydraulic processes in Full-scale Emplacement experiment. *Applied Thermal Engineering, 245,* 122836. https://doi.org/10.1016/j.applthermaleng.2024.122836

70. Li, Z., Luo, H., Jiang, Y., Liu, H., Xu, L., Cao, K. et al. (2024). Comprehensive review and future prospects on chip-scale thermal management: Core of data center's thermal management. *Applied Thermal Engineering, 251*, 123612. https://doi.org/10.1016/j.applthermaleng.2024.123612

71. Wang, J., Zhao, T. (2024). Medium spatiotemporal characteristics based global optimization method for energy efficiency trade-off issue in variable flow rate HVAC system. *Applied Thermal Engineering, 247,* 123132. https://doi.org/10.1016/j.applthermaleng.2024.123132

72. Chatterjee, A., Khovalyg, D. (2023). Dynamic indoor thermal environment using Reinforcement Learning-based controls: Opportunities and challenges. *Building and Environment, 244,* 110766. https://doi.org/10.1016/j.buildenv.2023.110766

73. Boinapalli, N. R. (2020). Digital transformation in us industries: Ai as a catalyst for sustainable growth. *NEXG AI Review of America, 1 (1),* 70–84.

74. Khan, O., Parvez, M., Seraj, M., Yahya, Z., Devarajan, Y., Nagappan, B. (2024). Optimising building heat load prediction using advanced control strategies and Artificial Intelligence for HVAC system. *Thermal Science and Engineering Progress, 49,* 102484. https://doi.org/10.1016/j.tsep.2024.102484

75. Olabi, A. G., Abdelghafar, A. A., Maghrabie, H. M., Sayed, E. T., Rezk, H., Radi, M. A. et al. (2023). Application of artificial intelligence for prediction, optimization, and control of thermal energy storage systems. *Thermal Science and Engineering Progress, 39,* 101730. https://doi.org/10.1016/j.tsep.2023.101730

76. Dinakarrao, S. M. P., Joseph, A., Haridass, A., Shafique, M., Henkel, J., Homayoun, H. (2019). Application and Thermal-reliability-aware Reinforcement Learning Based Multi-core Power Management. *ACM Journal on Emerging Technologies in Computing Systems, 15 (4),* 1–19. https://doi.org/10.1145/3323055

77. Shahid, A., Plaum, F., Korõtko, T., Rosin, A. (2024). AI Technologies and Their Applications in Small-Scale Electric Power Systems. *IEEE Access, 12,* 109984–110001. https://doi.org/10.1109/access.2024.3440067

78. Ahmad, T., Chen, H., Huang, R., Yabin, G., Wang, J., Shair, J. et al. (2018). Supervised based machine learning models for short, medium and long-term energy prediction in distinct building environment. *Energy, 158,* 17–32. https://doi.org/10.1016/j.energy.2018.05.169

79. Wang, Z., Hong, T., Piette, M. A. (2020). Building thermal load prediction through shallow machine learning and deep learning. *Applied Energy, 263,* 114683. https://doi.org/10.1016/j.apenergy.2020.114683

80. Hundi, P., Shahsavari, R. (2020). Comparative studies among machine learning models for performance estimation and health monitoring of thermal power plants. *Applied Energy, 265,* 114775. https://doi.org/10.1016/j.apenergy.2020.114775

81. Xiao, P., Ni, Z., Liu, D., Hu, Z. (2021). A power and thermal-aware virtual machine management framework based on machine learning. *Cluster Computing, 24 (3),* 2231–2248. https://doi.org/10.1007/s10586-020-03228-6

82. Lin, W., Wu, G., Wang, X., Li, K. (2020). An Artificial Neural Network Approach to Power Consumption Model Construction for Servers in Cloud Data Centers. *IEEE Transactions on Sustainable Computing, 5 (3),* 329–340. https://doi.org/10.1109/tsusc.2019.2910129

83. Chen, K.-C., Liao, Y.-H., Chen, C.-T., Wang, L.-Q. (2023). Adaptive Machine Learning-Based Proactive Thermal Management for NoC Systems. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 31 (8),* 1114–1127. https://doi.org/10.1109/tvlsi.2023.3282969

84. Patel, K., Mehta, N., Oza, P., Thaker, J., Bhise, A. (2024). Revolutionizing Data Centre Sustainability: The Role of Machine Learning in Energy Efficiency. *2024 IEEE International Conference on Interdisciplinary Approaches in Technology and Management for Social Innovation (IATMSI*), 1–6. https://doi.org/10.1109/iatmsi60426.2024.10503107

85. Erhan, L., Ndubuaku, M., Di Mauro, M., Song, W., Chen, M., Fortino, G., Bagdasar, O., Liotta, A. (2021). Smart anomaly detection in sensor systems: A multi-perspective review. *Information Fusion, 67,* 64–79. https://doi.org/10.1016/j.inffus.2020.10.001

86. Fan, C., Xiao, F., Li, Z., Wang, J. (2018). Unsupervised data analytics in mining big building operational data for energy efficiency enhancement: A review. *Energy and Buildings, 159,* 296–308. https://doi.org/10.1016/j.enbuild.2017.11.008

87. Bueno, A. M., Mendes da Luz, I., Niza, I. L., Broday, E. E. (2023). Hierarchical and K-means clustering to assess thermal dissatisfaction and productivity in university classrooms. *Building and Environment, 233,* 110097. https://doi.org/10.1016/j.buildenv.2023.110097

88. Surucu, O., Gadsden, S. A., Yawney, J. (2023). Condition Monitoring using Machine Learning: A Review of Theory, Applications, and Recent Advances. *Expert Systems with Applications, 221,* 119738. https://doi.org/10.1016/j.eswa.2023.119738

89. Schneider, T., Bedrikow, A. B., Stahl, K. (2024). Enhanced prediction of thermo-mechanical systems using machine learning, PCA, and finite element simulation. *Advanced Modeling and Simulation in Engineering Sciences, 11 (1).* https://doi.org/10.1186/s40323-024-00268-0

90. Zhou, X., Du, H., Xue, S., Ma, Z. (2024). Recent advances in data mining and machine learning for enhanced building energy management. *Energy, 307,* 132636. https://doi.org/10.1016/j.energy.2024.132636

91. Zhu, S., Lu, W., Feng, Y., Sun, C. (2024). Energy Optimization for Building Energy Management with Thermal Storage: A Multi-Agent Deep Reinforcement Learning Approach. *2024 43rd Chinese Control Conference (CCC),* 2805–2812. https://doi.org/10.23919/ccc63176.2024.10661808

92. Zhang, Z., Lam, K. P. (2018). Practical implementation and evaluation of deep reinforcement learning control for a radiant heating system. *Proceedings of the 5th Conference on Systems for Built Environments,* 148–157. https://doi.org/10.1145/3276774.3276775

93. Ortiz, Y., Arévalo, P., Peña, D., Jurado, F. (2024). Recent Advances in Thermal Management Strategies for Lithium-Ion Batteries: A Comprehensive Review. *Batteries, 10 (3),* 83. https://doi.org/10.3390/batteries10030083

94. Vamvakas, D., Michailidis, P., Korkas, C., Kosmatopoulos, E. (2023). Review and Evaluation of Reinforcement Learning Frameworks on Smart Grid Applications. *Energies, 16 (14),* 5326. https://doi.org/10.3390/en16145326

95. Shi, Z., Zheng, R., Zhao, J., Shen, R., Gu, L., Liu, Y. et al. (2024). Towards various occupants with different thermal comfort requirements: A deep reinforcement learning approach combined with a dynamic PMV model for HVAC control in buildings. *Energy Conversion and Management, 320,* 118995. https://doi.org/10.1016/j.enconman.2024.118995

96. Ran, Y., Hu, H., Wen, Y., Zhou, X. (2023). Optimizing Energy Efficiency for Data Center via Parameterized Deep Reinforcement Learning. *IEEE Transactions on Services Computing, 16 (2),* 1310–1323. https://doi.org/10.1109/tsc.2022.3184835

97. Chang, C.-W., Dinh, N. T. (2019). Classification of machine learning frameworks for data-driven thermal fluid models. *International Journal of Thermal Sciences, 135,* 559–579. https://doi.org/10.1016/j.ijthermalsci.2018.09.002

98. Li, A., Weng, J., Yuen, A. C. Y., Wang, W., Liu, H., Lee, E. W. M. et al. (2023). Machine learning assisted advanced battery thermal management system: A state-of-the-art review. *Journal of Energy Storage, 60,* 106688. https://doi.org/10.1016/j.est.2023.106688

99. Ababei, C., Moghaddam, M. G. (2019). A Survey of Prediction and Classification Techniques in Multicore Processor Systems. *IEEE Transactions on Parallel and Distributed Systems, 30 (5),* 1184–1200. https://doi.org/10.1109/tpds.2018.2878699

ISSN-L 2664-9969; E-ISSN 2706-5448

100. Kirchgässner, W., Wallscheid, O., Böcker, J. (2023). Thermal neural networks: Lumped-parameter thermal modeling with state-space machine learning. *Engineering Applications of Artificial Intelligence, 117,* 105537. https://doi.org/10.1016/j.engappai.2022.105537

101. Aparna, R., Idicula, S. M. (2022). Spatio-Temporal Data Clustering using Deep Learning: A Review. *2022 IEEE International Conference on Evolving and Adaptive Intelligent Systems (EAIS),* 1–10. https://doi.org/10.1109/eais51927.2022.9787701

102. Werner, D., Juretus, K., Savidis, I., Hempstead, M. (2018). Machine Learning on the Thermal Side-Channel: Analysis of Accelerator-Rich Architectures. *2018 IEEE 36th International Conference on Computer Design (ICCD),* 83–91. https://doi.org/10.1109/iccd.2018.00022

103. Ukiwe, E. K., Adeshina, S. A., Jacob, T., Adetokun, B. B. (2024). Deep learning model for detection of hotspots using infrared thermographic images of electrical installations. *Journal of Electrical Systems and Information Technology, 11 (1).* https://doi.org/10.1186/s43067-024-00148-y

104. Zhao, X., Zhao, Y., Hu, S., Wang, H., Zhang, Y., Ming, W. (2023). Progress in Active Infrared Imaging for Defect Detection in the Renewable and Electronic Industries. *Sensors, 23 (21),* 8780. https://doi.org/10.3390/s23218780

105. King, M., Woo, S. I., Yune, C.-Y. (2024). Utilizing a CNN-RNN machine learning approach for forecasting time-series outlet fluid temperature monitoring by long-term operation of BHEs system. *Geothermics, 122,* 103082. https://doi.org/10.1016/j.geothermics.2024.103082

106. Deepak, G., Parthiban, M., Nath, Srigitha, S., Sulaiman Alfurhood, B., Mouleswararao, B., Ravi Kishore, V. (2024). Ai-enhanced thermal modeling for integrated process-product-system optimization in zero-defect manufacturing chains. *Thermal Science and Engineering Progress, 55,* 102945. https://doi.org/10.1016/j.tsep.2024.102945

107. Chike, O. G., Ahmad, N., Faiz Wan Ali, W. F. (2024). Neural network prediction of thermal field spatiotemporal evolution during additive manufacturing: an overview. *The International Journal of Advanced Manufacturing Technology, 134 (5-6),* 2107–2128. https://doi.org/10.1007/s00170-024-14256-6

108. Szymanik, B., Psuj, G., Hashemi, M., Lopato, P. (2021). Detection and Identification of Defects in 3D-Printed Dielectric Structures via Thermographic Inspection and Deep Neural Networks. *Materials, 14 (15),* 4168. https://doi.org/10.3390/ma14154168

109. Wu, S.-H., Tariq, U., Joy, R., Mahmood, M. A., Malik, A. W., Liou, F. (2024). A Robust Recurrent Neural Networks-Based Surrogate Model for Thermal History and Melt Pool Characteristics in Directed Energy Deposition. *Materials, 17 (17),* 4363. https://doi.org/10.3390/ma17174363

110. Eivazi, H., Guastoni, L., Schlatter, P., Azizpour, H., Vinuesa, R. (2021). Recurrent neural networks and Koopman-based frameworks for temporal predictions in a low-order model of turbulence. *International Journal of Heat and Fluid Flow, 90,* 108816. https://doi.org/10.1016/j.ijheatfluidflow.2021.108816

111. Drgoňa, J., Tuor, A. R., Chandan, V., Vrabie, D. L. (2021). Physics-constrained deep learning of multi-zone building thermal dynamics. *Energy and Buildings, 243,* 110992. https://doi.org/10.1016/j.enbuild.2021.110992

112. Cheng, Y., Huang, Y., Pang, B., Zhang, W. (2018). ThermalNet: A deep reinforcement learning-based combustion optimization system for coal-fired boiler. *Engineering Applications of Artificial Intelligence, 74,* 303–311. https://doi.org/10.1016/j.engappai.2018.07.003

113. Akhsham, M., Dousti, M. J., Safari, S. (2025). Neural Network-Based Control of Forced-Convection and Thermoelectric Coolers. *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 44 (2),* 582–591. https://doi.org/10.1109/tcad.2024.3438689

114. Li, M., Dai, L., Hu, Y. (2022). Machine Learning for Harnessing Thermal Energy: From Materials Discovery to System Optimization. *ACS Energy Letters, 7 (10),* 3204–3226. https://doi.org/10.1021/acsenergylett.2c01836

115. Zhang, B., Hu, W., Cao, D., Huang, Q., Chen, Z., Blaabjerg, F. (2019). Deep reinforcement learning–based approach for optimizing energy conversion in integrated electrical and heating system with renewable energy. *Energy Conversion and Management, 202,* 112199. https://doi.org/10.1016/j.enconman.2019.112199

116. Ashayeri, M., Abbasabadi, N. (2024). A Hybrid Physics-Based Machine Learning Approach for Integrated Energy and Exposure Modeling. *Artificial Intelligence in Performance-Driven Design,* 57–79. https://doi.org/10.1002/9781394172092.ch3

117. Anwar, A., Talha, M., Hameed, A. (2023). *Application of Artificial Intelligence in Thermal Management and Wavelet Analysis: A Comprehensive Review.* https://doi.org/10.31219/osf.io/d2vn3

118. Ali, S. A., Habib, K., Younas, M., Rahman, S., Das, L., Rubbi, F. et al. (2024). Advancements in Thermal Energy Storage: A Review of Material Innovations and Strategic Approaches for Phase Change Materials. *Energy & Fuels, 38 (20),* 19336–19392. https://doi.org/10.1021/acs.energyfuels.4c03634

119. Sadeghi, G. (2022). Energy storage on demand: Thermal energy storage development, materials, design, and integration challenges. *Energy Storage Materials, 46,* 192–222. https://doi.org/10.1016/j.ensm.2022.01.017

120. Chekifi, T., Boukraa, M., Benmoussa, A. (2024). Artificial Intelligence for Thermal Energy Storage Enhancement: A Comprehensive Review. *Journal of Energy Resources Technology, 146 (6).* https://doi.org/10.1115/1.4065197

121. Bandhu, D., Khadir, M. D., Kaushik, A., Sharma, S., Ali, H. A., Jain, A. (2023). Innovative Approaches to Thermal Management in Next-Generation Electronics. *E3S Web of Conferences, 430,* 01139. https://doi.org/10.1051/e3sconf/202343001139

122. Lodhi, S. K., Hussain, H. K., Hussain, I. (2024). Using AI to Increase Heat Exchanger Efficiency: An Extensive Analysis of Innovations and Uses. *International Journal of Multidisciplinary Sciences and Arts, 3 (4),* 1–14. https://doi.org/10.47709/ijmdsa.v3i4.4617

123. Sabegh, M. (2022). *Deep Reinforcement Learning and Model Predictive Control Approaches for the Scheduled Operation of Domestic Refrigerators.* [PhD thesis; University of Lincoln].

124. Ghalkhani, M., Habibi, S. (2022). Review of the Li-Ion Battery, Thermal Management, and AI-Based Battery Management System for EV Application. *Energies, 16 (1),* 185. https://doi.org/10.3390/en16010185

125. Nasiri, M., Hadim, H. (2024). Advances in battery thermal management: Current landscape and future directions. *Renewable and Sustainable Energy Reviews, 200,* 114611. https://doi.org/10.1016/j.rser.2024.114611

126. Cao, K., Li, Z., Luo, H., Jiang, Y., Liu, H., Xu, L. et al. (2024). Comprehensive review and future prospects of multi-level fan control strategies in data centers for joint optimization of thermal management systems. *Journal of Building Engineering, 94,* 110021. https://doi.org/10.1016/j.jobe.2024.110021

127. Nadjahi, C., Louahlia, H., Lemasson, S. (2018). A review of thermal management and innovative cooling strategies for data center. *Sustainable Computing: Informatics and Systems, 19,* 14–28. https://doi.org/10.1016/j.suscom.2018.05.002

128. Weinstein, J. (2023). *Semiconductors and the calculation of the balance of power.* Available at: https://knowledge.uchicago.edu/nanna/record/6118/files/Semiconductors%20and%20the%20Calculation%20of%20the%20Balance%20of%20Power.pdf?withWatermark=0&withMetadata=0&registerDownload=1&version=1

129. Hosseinimotlagh, S., Enright, D., Shelton, C. R., Kim, H. (2021). Data-Driven Structured Thermal Modeling for COTS Multi-core Processors. *2021 IEEE Real-Time Systems Symposium (RTSS),* 201–213. https://doi.org/10.1109/rtss52674.2021.00028

130. Hirtz, T., Tian, H., Shahzad, S., Wu, F., Yang, Y., Ren, T.-L. (2024). Deep reinforcement learning framework for end-to-end semiconductor process control. *Neural Computing and Applications, 36 (20),* 12443–12460. https://doi.org/10.1007/s00521-024-09710-1

131. Radamson, H. H., Zhu, H., Wu, Z., He, X., Lin, H., Liu, J. et al. (2020). State of the Art and Future Perspectives in Advanced CMOS Technology. *Nanomaterials, 10 (8),* 1555. https://doi.org/10.3390/nano10081555

132. Fassi, Y., Heiries, V., Boutet, J., Boisseau, S. (2024). Toward Physics-Informed Machine-Learning-Based Predictive Maintenance for Power Converters – A Review. *IEEE Transactions on Power Electronics, 39 (2),* 2692–2720. https://doi.org/10.1109/tpel.2023.3328438

133. Buffa, S., Fouladfar, M. H., Franchini, G., Lozano Gabarre, I., Andrés Chicote, M. (2021). Advanced Control and Fault Detection Strategies for District Heating and Cooling Systems – A Review. *Applied Sciences, 11 (1),* 455. https://doi.org/10.3390/app11010455

134. Zhang, Y., Zhao, Y., Dai, S., Nie, B., Ma, H., Li, J. et al. (2022). Cooling technologies for data centres and telecommunication base stations – A comprehensive review. *Journal of Cleaner Production, 334,* 130280. https://doi.org/10.1016/j.jclepro.2021.130280

135. Suryadevara, S. (2021). Energy-proportional computing: Innovations in data center efficiency and performance optimization. *International Journal,* 44–64.

136. Li, Y., Wen, Y., Tao, D., Guan, K. (2020). Transforming Cooling Optimization for Green Data Center via Deep Reinforcement Learning. *IEEE Transactions on Cybernetics, 50 (5),* 2002–2013. https://doi.org/10.1109/tcyb.2019.2927410

137. Biswas, P., Rashid, A., Biswas, A., Nasim, M. A. A., Chakraborty, S., Gupta, K. D., George, R. (2024). AI-driven approaches for optimizing power consumption: a comprehensive survey. *Discover Artificial Intelligence, 4 (1).* https://doi.org/10.1007/s44163-024-00211-7

138. Velayutham, A. (2019). Ai-driven storage optimization for sustainable cloud data centers: Reducing energy consumption through predictive analytics, dynamic storage scaling, and proactive resource allocation. *Sage Science Review of Applied Machine Learning, 2 (2),* 57–71.

139. Dadashi, S., Aghasi, A. (2024). Thermal-aware virtual machine placement approaches: A survey. *Journal of Mahani Mathematical Research Center, 13 (2).*

140. Gu, J. (2023). *Characterization and modelling of resource usage and energy consumption in hpc datacenters by machine learnin.* [Master Thesis; University of Amsterdam].

141. Boppana, V. R. (2023). Data Analytics for Predictive Maintenance in Healthcare Equipment. *EPH-International Journal of Business & Management Science, 9 (2),* 26–36. https://doi.org/10.53555/eijbms.v10i1.176

142. Casado-Vara, R., Vale, Z., Prieto, J., Corchado, J. M. (2018). Fault-Tolerant Temperature Control Algorithm for IoT Networks in Smart Buildings. *Energies, 11 (12),* 3430. https://doi.org/10.3390/en11123430

143. Balali, Y., Chong, A., Busch, A., O'Keefe, S. (2023). Energy modelling and control of building heating and cooling systems with data-driven and hybrid models – A review. *Renewable and Sustainable Energy Reviews, 183,* 113496. https://doi.org/10.1016/j.rser.2023.113496

144. Pattyam, S. P. (2020). Ai in data science for predictive analytics: Techniques for model development, validation, and deployment. *Journal of Science & Technology, 1 (1),* 511–552.

145. Latapy, A., Ferret, Y., Testut, L., Talke, S., Aarup, T., Pons, F., Jan, G., Bradshaw, E., Pouvreau, N. (2022). Data rescue process in the context of sea level reconstructions: An overview of the methodology, lessons learned, up-to-date best practices and recommendations. *Geoscience Data Journal, 10 (3),* 396–425. https://doi.org/10.1002/gdj3.179

146. Liang, W., Tadesse, G. A., Ho, D., Fei-Fei, L., Zaharia, M., Zhang, C., Zou, J. (2022). Advances, challenges and opportunities in creating data for trustworthy AI. *Nature Machine Intelligence, 4 (8),* 669–677. https://doi.org/10.1038/s42256-022-00516-1

147. Shah, V., Konda, S. R. (2021). Neural networks and explainable ai: Bridging the gap between models and interpretability. *International Journal of Computer Science and Technology, 5 (2),* 163–176.

148. Chen, Z., Xiao, F., Guo, F., Yan, J. (2023). Interpretable machine learning for building energy management: A state-of-the-art review. *Advances in Applied Energy, 9,* 100123. https://doi.org/10.1016/j.adapen.2023.100123

149. Buah, E. (2022). *Artificial intelligence technology acceptance framework for energy systems analysis.* Available at: https://lutpub.lut.fi/handle/10024/163686

150. Sheriffdeen, K. (2024). *Physics-based simulation-assisted machine learning for estimating engineering system failure durations.* Available at: https://easychair.org/publications/preprint/nHDK

151. Kasaraneni, R. K. (2020). AI-enhanced energy management systems for electric vehicles: Optimizing battery performance and longevity. *Journal of Science & Technology, 1 (1),* 670–708.

152. Modupe, O. T., Otitoola, A. A., Oladapo, O. J., Abiona, O. O., Oyeniran, O. C., Adewusi, A. O., et al. (2024). Reviewing the transformational impact of edge computing on real-time data processing and analytics. *Computer Science & IT Research Journal, 5 (3),* 693–702. https://doi.org/10.51594/csitrj.v5i3.929

TECHNOLOGY AND SYSTEM OF POWER SUPPLY

DOI: 10.15587/2706-5448.2025.322457

OPTIMIZATION OF PUMP JACK ELECTRIC DRIVE OPERATION TAKING INTO ACCOUNT RESERVOIR FLOW RATE

pages 75–78

Andriy Malyar, *Doctor of Technical Sciences, Professor, Department of Electromechatronics and Computerised Electromechanical Systems, Lviv Polytechnic National University, Lviv, Ukraine, e-mail: andrii.v.maliar@lpnu.ua, ORCID: https://orcid.org/0000-0001-7735-0592*

Mykola Malyar, *Department of Computer Design Systems, Lviv Polytechnic National University, Lviv, Ukraine, ORCID: https://orcid.org/0000-0003-2688-8004*

The object of the study are the processes occurring in electric drives of sucker rod pumping units, which are used for mechanical oil production.

When designing oil pumping units, one of the issues is the synthesis of control systems for the electric drives of pump jacks. In the synthesis of the control system, it is important to take into account as many factors as possible that influence the performance of the well and its equipment. When synthesizing the criterion for optimal operation of the system, it is necessary to take into account changes in the technical condition of the oil production facility and the conditions of the reservoir operation. This is implemented using a control system that adjusts the electric drive speed according to the real operating conditions of the well. This approach allows improving the productivity of the oil pumping unit and increasing its economic efficiency.

The main focus is on the synthesis of a control system for the electric drive of a pump jack, which makes it possible to balance the intensity of fluid inflow into the well and its withdrawal. An optimization criterion is proposed, which takes into account different fluid inflow rates, thus adapting the electric drive operation to the specific conditions of each well.

The study used the theory of classical variational calculus. To find the minimum of the functional, and therefore the optimal parameters of the control system, a quadratic form, which is a Lyapunov function, was used.

The study resulted in the formulae for calculating the key operational parameters of the pump jack electric drive. The synthesized optimization criterion links the unit's productivity to parameters such as the number of crankshaft rotations, the rod pump delivery coefficient, and the load torque of the drive motor.

In practice, the proposed optimization criterion for the electric drive operation will enable improving the efficiency of the oil pumping unit through the rational selection of the drive motor's speed and torque. This, in turn, will enhance the well's operating conditions and extend its operational life.

Keywords: sucker rod pumping unit, optimization criterion, control system, pump jack, electric drive, well, functional.

References

1. Boiko, V. S. (2004). *Rozrobka ta ekspluatatsiia naftovykh rodovyshch.* Kyiv: Real Print, 695.
2. Liu, T., Tian, X., Liu, L., Gu, X., Zhao, Y., Zhang, L., Song, X. (2022). Modeling the Submergence Depth of Oil Well States and Its Applications. *Applied Sciences, 12 (23),* 12373. https://doi.org/10.3390/app122312373
3. Tan, C., Feng, Z.-M., Liu, X., Fan, J., Cui, W., Sun, R., Ma, Q. (2020). Review of variable speed drive technology in beam pumping units for energy-saving. *Energy Reports, 6,* 2676–2688. https://doi.org/10.1016/j.egyr.2020.09.018
4. Feng, Z.-M., Guo, C., Zhang, D., Cui, W., Tan, C., Xu, X., Zhang, Y. (2020). Variable speed drive optimization model and analysis of comprehensive performance of beam pumping unit. *Journal of Petroleum Science and Engineering, 191,* 107155. https://doi.org/10.1016/j.petrol.2020.107155
5. Peng, L., Zeng-Xiu, Z., Chao, W., Yi-Hui, Z. (2014). Research on Fuzzy PI Control Based on Genetic Algorithms for Beam Pumping Unit. *2014 Fourth International Conference on Instrumentation and Measurement, Computer, Communication and Control.* Harbin 72–76. https://doi.org/10.1109/imccc.2014.23

ISSN-L 2664-9969; E-ISSN 2706-5448

6. Barskii, V. A., Kurdiumov, D. S. (2003). Ispolzovanie avtomatizirovannogo reguliruemogo elektroprivoda v sostave stantcii upravleniia shtangovoi glubinnonasosnoi ustanovki. *Vestnik NTU KhPI "Problemy avtomatizirovannogo elektroprivoda. Teoriia i praktika", 10 (1),* 284.
7. Li, W., Vaziri, V., Aphale, S. S., Dong, S., Wiercigroch, M. (2021). Energy saving by reducing motor rating of sucker-rod pump systems. *Energy, 228,* 120618. https://doi.org/10.1016/j.energy.2021.120618
8. Pozdeev, D. A., Kudriavtcev, S. V. (2008). Intellektualnaia stantciia ALC800 kompanii ABB dlia upravleniia stankami-kachalkami. *Vestnik NTU KhPI "Problemy avtomatizirovannogo elektroprivoda. Teoriia i praktika", 30,* 265–268.
9. Elmer, W. G., Elmer, J. B. (2016). Pump Stroke Optimization: Case Study of Twenty Well Pilot. *SPE North America Artificial Lift Conference and Exhibition.* The Woodlands. Texas. https://doi.org/10.2118/181228-ms
10. Lei, D., Huang, X., Zhang, H., Yao, M., Chen, R., Liu, J. (2019). Optimization and Application of Reciprocating Direct-Drive Electric Submersible Plunger Pump Lifting System in the Xinjiang Oilfield. *The Open Chemical Engineering Journal, 13 (1),* 68–80. https://doi.org/10.2174/1874123101913010068
11. Popovych, M. H., Lozynskyi, O. Yu., Klepikov, V. B. et al.; Popovych, M. H., Lozynskyi, O. Yu. (Eds.) (2005). *Elektromekhanichni systemy avtomatychnoho keruvannia ta elektropryvody*. Kyiv: Lybid, 680.
12. Sugimoto, H., Koyama, M., Yano, M., Ohno, E. (1983). A new transfer function of an induction motor driven by variable frequency source. *1983 IEEE Power Electronics Specialists Conference,* 102–110. https://doi.org/10.1109/pesc.1983.7069845
13. Yuan, R.-S., Ma, Y.-A., Yuan, B., Ao, P. (2014). Lyapunov function as potential function: A dynamical equivalence. *Chinese Physics B, 23 (1),* 010505. https://doi.org/10.1088/1674-1056/23/1/010505
14. Lozynskyi, O. Yu., Lozynskyi, A. O., Marushchak, Ya. Yu. et al. (2016). *Syntez liniinykh optymalnykh dynamichnykh system.* Lviv: Vyd-vo Lvivskoi politekhniky, 932.