ENVIRONMENTAL AND BIOMATERIAL SCIENCES			
A. Povinné kurzy (Compulsory courses)	**B. Povinně volitelné teoretické kurzy (Compulsory optional courses)**	**C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)**	**D. Povinně volitelné doplňkové kurzy (Optional courses)**
Conference participation	Advances in biotechnology	Laboratory I – Cleanroom	Climate change: Influencing factors and impacts on ecosystem services
Doctoral seminar I, II, and III	Advanced biophysical methods in nanomaterial research	Laboratory II – Circular chemistry	High-energy X-ray (synchrotron-based X-ray) analyses
International internship	Advances in the application of analytical techniques	Laboratory III – ISO certified analytical measurements	Life-cycle assessment – Sustainable and eco-informed selection of materials
Publication and dissemination	Advances in the characterization techniques of materials	Laboratory IV – Advanced microscopy of materials	Mitigation of pollution and toxicity in the environment
Thesis preparation I, II, III, and IV	Chemistry and physics of surfaces and interfaces	Laboratory V – Synthesis of emerging inorganic materials	Molecular and cell biology for material research
Workshop/summer school	Hydrodynamics	Laboratory VI – Synthesis of emerging organic materials	Principles of circular economy
	Ion-beam synthesis and radiation testing of materials for energetic applications	Laboratory VII – Biomedical and immunology testing	Professional and academic German for scientists
	Luminescence: From molecules to nanoparticles	Laboratory VIII – Application-oriented testing of materials	
	Magnetic properties of functional materials	Laboratory IX – Computational modelling of particle materials and fluid dynamics	
	Materials and living systems		
	Materials and principles of energy storage and conversion		
	Materials for tissue engineering and medical use		
	Materials modelling		
	Materials under extreme conditions		
	Microbiology in material research		
	Porous materials		
	Powders and granular materials		

C. POVINNĚ VOLITELNÉ PRAKTICKÉ KURZY (SPECIALIZED LABORATORIES AND PRACTICALS)

B-III – Course details

Course title	**Laboratory I – Cleanroom**				
Type	C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)			**Recommended year**	1-2
Course length	12L + 32l	**Hours**	44	**Credits**	20
Course completion	Pre-exam credit, exam			**Teaching type**	Lectures, laboratory
Verification	Pre-exam credit: laboratory protocols Written exam				
Guarantor	**Mgr. Marcel Štofik, PhD.**				
Lecture(s)	Mgr. Marcel Štofik, PhD.				
Syllabus					

Motivation

Microtechnology processes are one of the essential tools for the development of advanced and smart technologies in fields such as biology, chemistry, biochemistry, bio- and nano-technology, or environmental science. They have the potential to bring new ideas and provide new approaches that students can apply in their work during their studies and in their professional lives. By learning microtechnology with practical tasks, students will gain a practical core understanding of the technology and new skills and knowledge to improve their work.

Objectives

The aim of the course is to learn the basic rules of behaviour and work in a dust-free environment (Fig. 1) and to learn basic skills with available laboratory instruments and machines installed in the clean room facility of the faculty. The course will include practical activities based on model tasks. Practical tasks will teach students the basic principles of selected methods and the basics of technology necessary for independent work with selected laboratory equipment. Through hands-on activities, students will learn selected microtechnology processes related to microdevice fabrication and metrology concepts. The output of the internship will be a technical report based on activities carried out in the laboratory during the course.

Fig. 1. Cleanroom facility located in Fauclty of Science UJEP.

Acquired skills and knowledge

Students will gain core practical skills and theoretical knowledge of the selected technologies. They will acquire designing skills for selected software utilities to transform their ideas into digital sketches and 3D models. Students will be able to prepare digital data for patterning and fabrication of designed solutions. Students will be able to prepare and clean substrates before processing and adjust material deposition and baking conditions to adjust the overall microfabrication process. Students will be able to plan and perform multilevel processes with alignment marks for nano- and micro-fabrication. Based on the material used and subsequent processes, they will be able to select the best solutions for patterning with knowledge of the advantages and disadvantages of the selected patterning technique. Students will be skilled in designing and planning the processes for the fabrication of microstructures into silicon substrates and to transfer them into polymeric materials. Students will be able to fabricate microelectrodes, cut, drill, and format silicon and glass substrates, and use optimal strategies for bonding selected substrates. Students will be skilled in fabricating simple, ready-to-use solutions for testing or further development under the operator's supervision.

The theoretical and practical parts of the course will cover the following topics.

1. Short introduction to microfabrication processes – patterning, additive and subtractive processes, solidification and reshaping of polymers, processes designing, introduction to designing software.
2. Clean room environment – good laboratory practice. The importance of cleanrooms, basic standards, clothing for cleanrooms, movement in a dust-free environment, handling objects, cleaning, waste management, laboratory conditions such as temperature, humidity, need for filtration, etc.
3. Deposition of polymeric materials by spin-coating.
    a. Preparation and cleaning of substrates,
    b. Deposition of polymers under specific conditions (different polymer viscosities, deposition based on selected process parameters - acceleration speed, target spinning speed, process time, EBR process),
    c. Polymers baking (softbake, post-exposure bake, hardbake),
    d. Characterization of deposited material (processed by UV or laser lithography) by optical microscopy, SEM and profilometry.
4. Serial microfabrication patterning processes.
    a. Exposure of polymer materials by a focused laser beam (microns-sized features),
    b. Exposure of polymer materials by a focused electron beam (submicron-sized features),
    c. Characterization of patterned microstructures by optical microscopy, SEM and profilometry methods.
5. UV lithography patterning processes.
    a. UV lithography methods such as flood exposure, mask exposure, and exposure with alignment explanation for multilevel processes,
    b. Hardcontact, softcontact, proximity contact modes for lithography,
    c. Overview of UV imprint and soft lithography processes,
    d. Characterization of patterned material by optical microscopy, SEM and profilometry.
6. Processes provided by bonder.
    a. Selected substrates bonding techniques – performance of material bonding will be presented on selected material types (polymers, glass and silicon substrates,
    b. Hot embossing of thermoplastic polymers,
    c. Characterization of patterned material by optical microscopy and SEM.
7. Deposition of thin metal layers.
    a. Metallization of substrates by magnetron sputtering and metal evaporation processes,
    b. Selective wet metal etching based on generated micropatterns by lithography,
    c. Characterization of deposited material by optical microscopy, SEM and profilometry.
8. Plasma processes for etching and modification of substrate (wafer) surfaces.
    a. Deep reactive ion etching of silicon substrates, including the Bosh process,
    b. O_2 plasma etching (ashing), O_2 surface "activation", plasma deposition of polymers,
    c. Characterization of material by optical microscopy, SEM, profilometry.
9. Powder blasting technology – rapid technology for structuring hard materials.
10. Soft lithography – performance of casting microtechnology processes.

Literature

1. S. Franssila, *Introduction to Microfabrication*, 2^{nd} Ed., Wiley, (2010).
2. M. J. Madou, *Fundamentals of Microfabrication and Nanotechnology. Volume II, Manufacturing Techniques for Microfabrication and Nanotechnology*, 3^{rd} Ed., CRC Press, (2012).
3. B. Bhattacharyya, B. Doloi, *Modern Machining Technology: Advanced, Hybrid, Micromachining and Super Finishing Technology*, Academic Press, (2020).

B-III – Course details

Course title	**Laboratory II – Circular chemistry**				
Type	C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)			**Recommended year**	1-2
Course length	24l	**Hours**	24	**Credits**	20
Course completion	Pre-exam credit			**Teaching type**	laboratory
Verification	Active approach to the task Fulfilling the assigned task Laboratory protocols				
Guarantor	**doc. Dr. Ing. Pavel Kuráň**				
Lecture(s)	doc. Dr. Ing. Pavel Kuráň Ing. Ivana Barchánková, Ph.D. Ing. Lucie Oravová, Ph.D. Ing. Pavol Midula, Ph.D.				

Syllabus

The laboratory is primarily focused on the chemical aspects of circular economy and its practical application. The main aim is to introduce modern techniques used in waste (plastics, e-waste, biomass, textile fibres and other) transformation and characterization of secondary products. Students will gain knowledge about thermal and chemical decomposition of waste material. Those techniques include processes based on pyrolytic and solvolytic decomposition. Students will be trained in sample preparation for pyrolysis, sample transformation by pyrolysis-to-pyrolysis oil and sample pre-treatment for GC-MS analysis, work with micro laboratory pyrolysis unit directly connected to GC-MS (for direct characterization of pyrolysis products) and mass spectra data processing. Another set of experiments will include a process of solvolysis, sample precipitation, distillation and product characterization. The practical will be held in the laboratories of the Centre of Advanced Separation Techniques. Students will perform a selected set of laboratory experiments, deliver products and results of particular chemical recycling (pyrolysis, solvolysis) and separation (distillation, extraction) methods.

Motivation

Waste recycling is a hot topic and a great challenge for modern environmental technological research. Recycling processes represent important innovation and are a key aspect of the circular economy. The laboratory introduces students to two promising ways of waste recycling both of which offer solutions in environmental research regarding sustainability. Students will become experienced with the transformation of waste materials involving thermal and chemical treatments for usable secondary products.

Objectives

In the initial phase, students will learn how to prepare samples for pyrolysis experiments (pre-cleaning, grinding under N_2 atmosphere) and how to deal with pyrolysis products, such as pyrolysis oils, wax, their purification (distillation, extractions) for GC-MS analyses. Subsequently, students will learn the mechanism of organic reactions during the pyrolysis processes and the interpretation of MS spectra. They will learn and gain new knowledge in theory and practical application of solvolysis experiments including filtration, precipitation, purification and their use in the emerging area of waste treatment.

Acquired skills and knowledge

Students of the course will be able to apply obtained knowledge in the field of waste treatment, modern environmental research and analytical chemistry. They will be able to suggest optimised conditions for the pyrolysis processes of various types of waste with the expectation of desired products to be obtained. They will also become acquainted with the field of mass spectroscopy and interpreting mass spectra. They will get skills in analytical separation techniques such as distillation, filtration, purification, precipitation, and extraction.

Literature

1. R. E. Hester, R. M. Harrison, *Waste as a Resource. (Issues in Environmental Science and Technology)*, RSC Publishing, (2013).
2. RPA Europe. *Chemical Recycling of Polymeric Materials from Waste in the Circular Economy*, Final report prepared for the European Chemicals Agency (2021). Available online at: https://www.mpo.cz/assets/cz/prumysl/chemicke-latky-a-smesi/reach-povinnosti-a-informace/2021/11/Zprava-Chemicka-recyklace.pdf
3. J. Snow, J. Lederer, P. Kuran, P. Koutnik, Dechlorination during pyrolysis of plastics: Effect of municipal plastic waste composition. *Fuel Processing Technology* **248** (2023) 107823.

B-III – Course details

Course title	**Laboratory III – ISO certified analytical measurements**				
Type	C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)			**Recommended year**	1-2
Course length	40l	**Hours**	40	**Credits**	20
Course completion	Pre-exam credit			**Teaching type**	laboratory
Verification	Laboratory protocols				
Guarantor	**Ing. Jitka Tolaszová, Ph.D.**				
Lecture(s)	Ing. Jitka Tolaszová, Ph.D.				
Syllabus					

The laboratory practice would be held at the Health Institute in Ústí nad Labem, which has the status of an accredited laboratory.

In accordance with Section 16 of Act No. 22/1997 Coll., on Technical Requirements for Products, as amended, the Czech Accreditation Institute issued a "Certificate of Accreditation" for an experienced laboratory of the Centre of Hygienic Laboratories, Health Institute. The scope of the granted accreditation concerns the chemical, physical, and microbiological analysis of water, food, alcohol, peloids, biological materials, waste, asbestos, and air. Sensory analysis of water and food. The accreditation also concerns sampling techniques.

Analysis of extracts, solid materials, and smears. Toxicity tests. Measurement of environmental factors, and control of sterilizers and disinfectants. This certificate is a document of accreditation based on the assessment of compliance with accreditation requirements according to ČSN EN ISO/IEC 17025:2018

Motivation

The laboratory practical will be based on and predominantly reflect the theoretical knowledge learnt in the Compulsory Option A course "*Advances in the Applications of Analytical Techniques*", and Optional Courses "Technologies of Environmental Pollution, Toxicity and Risks Mitigation", and "*Climate Change: Influencing Factors and Impacts on Ecosystem Services*". Although undertaking the courses is not a prerequisite for enrolling in the practical.

As one of the most important institutions operating in the North Bohemian region as well as in the East Bohemian region in the field of environmental protection, the Health Institute monitors the content of foreign substances in the environment for a long-time during research on their migration, transformation, and impact on human health. The laboratories are mainly equipped to analyse trace concentrations of organic pollutants, such as pesticides, pharmaceuticals, PAHs, acrylamide, PCB, VOC, BTEX etc. These substances are determined either in liquid (water) or solid matrices (soil, sediment, food).

The practice will be carried out either in Ústi nad Labem or in Hradec Králové, both labs are equipped with complementary analyses, to meet the individual requirements and interests of doctoral students. The laboratories in Ústí nad Labem and Hradec Králové are equipped with modern instruments for the analysis of liquid and solid samples in environmental components, such as a 1290 Infinity II liquid chromatograph with a 6495 QQQ mass spectrometer from Agilent Technologies; a 1260 liquid chromatograph with a fluorescence detector from Agilent Technologies; a 6890 gas chromatograph with a 5975 mass spectrometer from Agilent Technologies; or with an electron capture detector (μECD) and with a flame ionization detector (FID) and ECD connected in parallel.

Objectives

The aim is to acquaint students practically with the functioning of an accredited laboratory, and to try working according to standard operating procedures required in commercial laboratories and industry. With the reception of samples, their collection, processing, analysis, and the delivery of the results to the customer. During sampling, students learn about general principles such as basic requirements (representativeness, homogeneity), sampling documentation, sampling plan, etc.

From the accredited exams, students will try the processing of samples for the determination of polar and non-polar pesticides, pharmaceuticals, PAHs in water, the determination of acrylamide in food, the measurement of these samples and the subsequent evaluation of the results.

As for pesticides, students will deal mainly with triazines, pyridazinones, chloroacetanilides, and their transformation products, which are among the herbicides and in the Czech Republic are widely used for crops such as sugar beet, corn, cereals and oilseed rape. Students carry on the measurements of organochlorine pesticides (OCP) (for example, alpha HCH, aldrin, β-HCH, δ-HCH, dieldrin, endosulfan, endosulfan sulfate, endrin, endrin aldehyde, γ-HCH, hexachlorobenzene, heptachlor, hepta chlorepoxide, cis-chlordane, trans-chlordane, isodrin, methoxychlor, mirex, o,p'-DDD, o,p'-DDE, o,p'-DDT, p,p'-DDD, p,p'-DDE, p,p'-DDT, oxychlordane), which were all banned in the 70s of the last century, but they can still be found in the environment. Pharmaceuticals in water will be mainly beta-lactam (e.g. amoxicillin) and macrolide antibiotics (e.g. erythromycin), antiepileptics (e.g. carbamazepine), anti-inflammatory pharmaceuticals (e.g. diclofenac), antidepressants (e.g. venlafaxine), pharmaceuticals for the treatment of diabetes (e.g. metformin), etc. For polar pesticides and pharmaceuticals, students will try their easy preparation using filtration. For non-polar pesticides (OCP), students will try their preparation with liquid-liquid extraction (LLE), as well as for PCB from water and with microwave-assisted extraction (MAE) from solid samples.

From PCB, we will deal with seven congeners (28, 52, 101, 118, 138 153, 180).

From VOC, we will focus mainly on o-, m-, p-dichlorbenzenes, 1,2-dichlorethane, chlorbenzene, 1,1,2,2-tetrachloroethene (TeCA), 1,1,2-trichlorethylene, chloroform, tetrachloromethane, bromoform, dibromochloromethane, dichloromethane, xylenes, styrene, toluene, ethylbenzene, 1,2,3-trichlorbenzene, 1,2,4-trichlorbenzene, 1,3,5-trichlorbenzene, dichloromethane, 1,2-dichlorethene, 1,1-dichlorethene, and vinylchlorid. Students will get acquainted with the Purge and Trap method, and solid-phase microextraction (SPME).

From PAHs, students will predominantly focus mainly on PAHs designated by the US Environment Protection Agency as priorities, which are often found in the environment, such as benzo(a)anthracene, fluoranthene, and pyrene (16 EPA PAHs). Students will get acquainted with the processed PAHs from water with SPE extraction.

When processing acrylamide from food, students will learn QuEChERS extraction, which is very efficient and fast.
They will become acquainted with the terminology of liquid chromatography in practice such as chromatogram description, separation efficiency, columns, and Van-Deemter equation, as well as with the terminology of fluorescence and mass detector. They will try the separation of approximately 140 analytes in one injection and the effect of individual mobile phases on the separation together with the use of suitable columns.

Acquired skill and knowledge
Students will learn work procedures in an accredited laboratory in the processing of water and food samples, measurement and evaluation, and at the same time work on modern devices. In theory, they become acquainted with the process of accreditation, method validation, interlaboratory tests, and communication with a variety of customers ranging from governmental bodies to private industry, etc.

Literature

1. ČSN EN ISO/IEC 17025:2018 Všeobecné požadavky na kompetenci zkušebních a kalibračních laboratoryí (General requirements for the competence of testing and calibration laboratories). (This is the newest and valid standard because newer has not been issued, yet)
2. ČSN EN 16618, 56 0601, prosinec 2015: Analýza potravin – Stanovení akrylamidu v potravinách kapalinovou chromatografií s tandemovou hmotnostní spektrometrií (LC-ESI-MS/MS). (Food analysis - Determination of acrylamide in food by liquid chromatography with tandem mass spectrometry (LC-ESI-MS/MS). (A newer standard has not been issued, yet)
3. A. Kruve *et al.*, Tutorial review on validation of liquid chromatography-mass spectrometry methods: Part I. *Anal. Chim. Acta* **870** (2015) 29. (A more thorough review on validation of LC-MS methods has not been issued, yet)
4. A. Kruve *et al.*, Tutorial review on validation of liquid chromatography-mass spectrometry methods: Part II. *Anal. Chim. Acta* **870** (2015), pp. 8. (A more thorough review of the validation of LC-MS methods has not been issued, yet)
5. T. Patil Dongare, *Good Laboratory Practices and Compliance Monitoring*, Pharmamed Press, (2021).
6. P. Deshmukh, *Principles of Good Laboratory Practice: Accreditation Process Requirements Paperbac*,. Adhyyan Books, (2020).
7. Web pages of Eurachem (a network of organisations in Europe having the objective of establishing a system for the international traceability of chemical measurements and the promotion of good quality practices. It provides a forum

for the discussion of common problems and for developing an informed and considered approach to both technical and policy issues. It provides a focus for analytical chemistry and quality related issues in Europe):

Online resources

Eurachem: Method validation; available at https://eurachem.org/index.php/mnu-tsk-mv
Eurachem: Measurement Uncertainty; available at https://eurachem.org/index.php/tskmu
Eurachem: Proficiency Testing; available at https://eurachem.org/index.php/tskpt

B-III – Course details

Course title	**Laboratory IV – Advanced microscopy of materials**				
Type	C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)			**Recommended year**	1-2
Course length	10L + 60l	**Hours**	70	**Credits**	20
Course completion	Pre-exam credit, exam			**Teaching type**	Lectures, laboratory
Verification	Laboratory protocols Written exam				
Guarantor	**Ing. Stanislav Vinopal, Ph.D.**				
Lecture(s)	Ing. Stanislav Vinopal, Ph.D., MSc. MSc. Dominika Wrobel, Ph.D. Mgr. Marcel Štofik, Ph.D. doc. Ing. Jiří Orava, Ph.D.				
Syllabus					

Motivation

The advanced microscopy of materials course will cover light, e-beam imaging (scanning-electron and transmission-electron microscopy), and atomic-force microscopy (AFM) hands-on experience. The course will offer a platform for participants to explore intricate cellular dynamics and material interactions. This course will provide students with essential tools and knowledge for probing living systems, engineering, environmental and biomaterials.

Objectives

The primary objective of this practical course is to equip participants with the proficiency to wield advanced microscopy techniques effectively. Through a combination of theoretical insights and dominant hands-on experience, participants will achieve the following goals:

Fluorescence microscopy mastery. Students will comprehend the principles underlying fluorescence microscopy and its variants, including cutting-edge methods. By grasping the intricacies of sample preparation for immunofluorescence and live imaging, participants will become adept at working with diverse biological samples.

Electron microscopy proficiency. Trainees will delve into the world of electron microscopy, gaining competence in both scanning electron microscopy (SEM) and transmission electron microscopy (TEM). From classic preparation techniques to modern cryo methods important for biological samples, students will explore the preparation and imaging of biological samples and materials at the greatest resolutions.

Atomic-force microscopy. Students will understand the methods of probing topography with modern imaging modes. They will learn how to probe and understand the mechanism of the nanomechanical response of materials and cells. Students will also understand the AFM artefacts (drift, tip damage, geometrical limitations, scanner errors and others), and learn how to identify them correctly to obtain reproducible data reflecting the real state of a sample.

Sample handling expertise. Students will learn the critical art of sample handling, ranging from coating surfaces for immunofluorescence to preparing biological samples for electron microscopy or AFM. This expertise is crucial for obtaining reliable and reproducible results.

Image Analysis and Processing. A comprehensive understanding of imaging extends beyond image acquisition. Students will gain proficiency in digital image processing, exploring basic image analysis methods such as particle analysis, elasticity mapping, composition mapping etc. This skill will enable them to extract meaningful quantitative data from microscopy images. This also concerns correct data interpretation.

Acquired skills and knowledge

Upon completing this hands-on training course, participants will possess a valuable set of skills and knowledge essential for advancing their careers in the field of environmental and biomaterial research:

Microscopy technique mastery. Participants will be adept at operating various microscopy techniques, including fluorescence microscopy, confocal microscopy, SEM, TEM, cryo-TEM, and AFM.

Sample preparation proficiency. Participants will be equipped to prepare diverse biological and different types of soft and hard materials for light, electron, and atomic microscopy.

Advanced Imaging Insight. Participants will possess insights into advanced imaging techniques, enabling them to select and apply the most appropriate method for specific research objectives.

The theoretical part of the course and the laboratory will be structured as follows.

1. Fluorescence microscopy
- Immunofluorescence - sample preparation (coating of various surfaces, biological samples),
- Live imaging - sample preparation (staining and transfection methods),
- 3D samples (e.g., organismal whole mounts, cancer spheroids) and their preparation, including optical clearing methods,
- Advanced light microscopy techniques (confocal, light sheet).

The following theoretical and practical aspects of trained methods will be discussed:
- Principles of fluorescence microscopy and its variants, including hardware construction (confocal, light sheet, total-internal reflection fluorescence-TIRF, stimulated emission depletion-STED, structured-illumination microscopy-SIM, stochastic optical reconstruction microscopy-STORM/Photoactivated Localization Microscopy-PALM, Lattice-light-sheet microscopy, and other selected methods),
- Principles of immunofluorescence, rules for working with antibodies, surface preparation,
- Principles of working with live cells, imaging media composition with a focus on cell metabolism, problematics of refractive indices matching, objective selection, fluorescence reporters, including recent advances in fluorescent protein and specific intracellular protein labelling by fluorescent dye technology.

2. Electron microscopy (biological and material sample preparation and imaging)
- SEM and TEM microscopy techniques,
- Cryo-TEM and cryo-SEM as advanced tools of electron microscopy,
- FIB-SEM as an advanced tool for electron microscopy sample preparation and 3D imaging.

During the practical work, the main issues related to the electron microscopy of biological samples will be addressed:
- Principles of electron microscopy, common and specific features of scanning and transmission electron microscopy,
- Transmission electron microscopy for material and life science. Characteristic properties of samples (samples for material and life science) with regard to their analysis in TEM electron microscopes. Standard methods of material preparation for the transmission electron microscope in life science (biological macromolecules, prokaryotic and eukaryotic cells and biological tissues) and material science (nanomaterials and bulk materials),
- Cryo-transmission electron microscopy as a modern tool for electron microscopy. Methods for cryo- samples preparation and cryo-TEM observation,
- Scanning electron microscopy for material and life science. Standard methods for preparation of samples (samples for material and life science) for a scanning electron microscope, Importance of critical point drying methods for biological material preparation. Recording of images by scanning electron microscope with specific electron detectors (SE, BSE, InLens, STEM). Using specific observation conditions (high and low vacuum observation),
- Cryo-scanning electron microscopy and its possibilities in biological applications. Basic methods for cryo-samples preparation and cryo-SEM observation,
- FIB-SEM as a tool for precise microscopy of cross-sections (surface polishing and dual beam mode observations) and 3D electron microscopy. Lamella preparation and set-up for transmission electron microscopy,

- Digital image recording and image processing in transmission and scanning electron microscopy, including basic methods of image analysis (e.g., particle size analysis). Principles of imaging and image processing for correlative electron microscopy.

3. **Atomic-force microscopy (biological or hard material sample preparation and imaging)**
   - AFM imaging (contact-, amplitude-, and force-based imaging modes),
   - Quantitative imaging of nanomechanical properties,
   - AFM as an advanced tool for imaging biological and hard samples.

The theoretical and practical aspects of AFM will be discussed:

- Principles of the imaging modes; understanding of the feedback circuit and its influence on image quality,
- Principles of forces interactions,
- Physics of imaging mechanical properties at nanoscale,
- Quantitative analysis of elastic moduli,
- Understanding of AFM artifacts.

Literature

1. J. I. Goldstein *et al.*, *Scanning Electron Microscopy and X-Ray Microanalysis*, Springer New York, (2018).
2. R. A. Fleck and B. M. Humbel, *Biological Field Emission Scanning Electron Microscopy*, 1st Ed., Wiley, (2019).
3. H. Schatten, ed., *Scanning Electron Microscopy for the Life Sciences*, Cambridge University Press, (2012).
4. A. Ul-Hamid, *A Beginners' Guide to Scanning Electron Microscopy*, Springer International Publishing, (2018).
5. B. Voigtländer, *Atomic Force Microscopy*, Springer International Publishing, (2019).
6. N. Yao, ed., *Focused Ion Beam Systems: Basics and Applications*, Cambridge University Press, (2011).
7. P. J. Goodhew *et al.*, eds., *Electron Microscopy and Analysis*, 3rd Ed., Taylor & Francis, (2000).
8. M. J. Dykstra and L. E. Reuss, *Biological Electron Microscopy*, Springer US, (2003).
9. C. B. Carter and D. B. Williams, eds., *Transmission Electron Microscopy*, Springer International Publishing, (2016).
10. Z. Luo, *A Practical Guide to Transmission Electron Microscopy: Fundamentals*, Momentum Press, (2016).
11. Z. Luo, *A Practical Guide to Transmission Electron Microscopy, Volume II*, Momentum Press, (2016).
12. A. Cavalier *et al.*, eds., *Handbook of Cryo-Preparation Methods for Electron Microscopy*, 1st Ed., CRC Press, (2008).
13. H. R. Ueda *et al.*, Tissue clearing and its applications in neuroscience. *Nat. Rev. Neurosci.* **21** (2020) 61.
14. M. T. Ke *et al.*, Super-resolution mapping of neuronal circuitry with an index-optimized clearing agent. *Cell Rep.* **14** (2016) 2718.
15. M. Pende *et al.*, A versatile depigmentation, clearing, and labeling method for exploring nervous system diversity. *Sci. Adv.* **6** (2020) eaba0365.

Online learning tools

Education in Microscopy and Digital Imaging: https://zeiss-campus.magnet.fsu.edu/
Electron Microscopy Learning Center: https://www.thermofisher.com/cz/en/home/electron-microscopy/learning-center.html
AFM: https://www.doitpoms.ac.uk/tlplib/afm/index.php
TEM: https://www.doitpoms.ac.uk/tlplib/tem/index.php
Optical Microscopy: https://www.doitpoms.ac.uk/tlplib/optical-microscopy/index.php
Indexing Electron Diffraction Patterns: https://www.doitpoms.ac.uk/tlplib/diffraction-patterns/index.php
Brillouin Zones: https://www.doitpoms.ac.uk/tlplib/brillouin_zones/index.php

B-III – Course details

Course title	**Laboratory V – Synthesis of emerging inorganic materials**				
Type	C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)			**Recommended year**	
Course length	80l	**Hours**	80	**Credits**	20
Course completion	Pre-exam credit			**Teaching type**	laboratory
Verification	Active approach to the task Fulfilling the assigned task Laboratory protocols				
Guarantor	**Mgr. Jan Hynek, Ph.D.**				
Lecture(s)	Mgr. Jan Hynek, Ph.D.				
Syllabus					

The laboratory practical will take 2 weeks. The laboratory will be carried out at the Institute of Inorganic Chemistry (IIC), Czech Academy of Science, which has long-term expertise in the synthesis, characterization and applications of porous hybrids, important materials used in various environmental applications. The practical content listed below is just a guideline for the possible work – laboratory tasks will be updated annually according to the latest trends and challenges. Practical will also reflect the student's research topic with an emphasis on individualization. IIC CAS is equipped with devices necessary for sensitive organic synthesis (Schlenk line, glove-box), solvothermal synthesis of porous hybrids (autoclaves, programmable ovens), and instruments for the characterization of organic compounds (NMR JEOL 600 MHz) and porous hybrids (PANalytical X'Pert PRO diffractometers, 3P Instruments adsorption analyser).

Motivation
Hybrid materials are widely studied group of compounds, which nowadays find use in many different fields including environmental applications, for example, for adsorption or catalytic degradation of various pollutants. In recent years, IIC CAS has published several papers on the synthesis of new structures of porous hybrids by using a unique class of organic ligands, their stability under the operational conditions of various applications, and applications of porous hybrids for the removal of pollutants from water. Therefore, IIC has relevant advanced expertise in the field of materials synthesis.

Objectives
During practical, students will be introduced to the preparation and characterization of ligands and porous hybrids. Students will learn the standard methods of synthesis (reactions under an inert atmosphere, Schlenk techniques), purification methods used for the isolation of compounds (column chromatography, crystallization methods), and the basics of nuclear magnetic resonance (NMR) spectroscopy as the most important method of characterization. Students will also learn the standard methods of synthesis of porous hybrids (solvothermal synthesis in autoclave under autogenous pressure) and the materials characterization (powder X-ray diffraction, measurement and analysis of gas adsorption isotherms).

Possible laboratory tasks the student may be involved in are the preparation of different derivatives of the methylester of 5,10,15,20-tetrakis(4-carboxyphenyl)porphyrin, metal complexes (e.g., Ni(II), Pd(II)), derivatives with substituents on beta-position of the porphyrin ring (formyl, hydroxymethyl, phosphonate etc.), and the deprotected carboxylic acid, which can be used for the synthesis of porous hybrids. Performing the syntheses, students will encounter different types of organic reactions (porphyrin condensation, metalation, Vilsmaier reaction, hydrolysis etc.). Alternatively, students will synthesize phosphinate ligands by using predominantly Pd(0)-catalysed P-C cross-coupling reactions. Students will further use the obtained organic ligands for the synthesis of respective porous hybrids. Students will study their basic properties (crystallinity, porosity). The particular laboratory tasks will be chosen individually according to the students' research topic and the ongoing research in the laboratory.

Acquired skills and knowledge
Students will learn the basic procedures used for the synthesis and characterization of hybrid materials. This includes methods of organic synthesis used for the preparation of ligands, common methods of characterization of organic compounds, especially NMR spectroscopy, solvothermal methods used for the synthesis of hybrid materials, and powder X-ray diffraction and adsorption measurements, which are used for the characterization of porous crystalline materials.

Literature	

1. S. Kaskel, *The Chemistry of Metal–Organic Frameworks: Synthesis, Characterization, and Applications*, Wiley-VCH Verlag, (2016).
2. P. J. Brothers, M. O. Senge, *Fundamentals of Porphyrin Chemistry: A 21st Century Approach*, John Wiley & Sons, Ltd., (2022).
3. S.-S. Bao, G. K. H. Shimizu, L.-M. Zheng, Proton conductive metal phosphonate frameworks. *Coord. Chem. Rev.* **378** (2019) 577.
4. S. J. I. Shearan *et al.*, New directions in metal phosphonate and phosphinate chemistry. *Crystals* **9** (2019) 270.
5. Z. Chen *et al.*, Reticular chemistry in the rational synthesis of functional zirconium cluster-based MOFs. *Coord. Chem. Rev*. **386** (2019), 32–49.

<table>
<tr><th colspan="7">B-III – Course details</th></tr>
<tr><td>Course title</td><td colspan="6">Laboratory VI – Synthesis of emerging organic materials</td></tr>
<tr><td>Type</td><td colspan="3">C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)</td><td colspan="2">Recommended year</td><td>1-2</td></tr>
<tr><td>Course length</td><td>80l</td><td>Hours</td><td>80</td><td>Credits</td><td colspan="2">20</td></tr>
<tr><td>Course completion</td><td colspan="3">Pre-exam credit</td><td>Teaching type</td><td colspan="2">laboratory</td></tr>
<tr><td>Verification</td><td colspan="6">Active approach to the task
Fulfilling the assigned task
Laboratory protocols</td></tr>
<tr><td>Guarantor</td><td colspan="6">RNDr. Karel Škoch, Ph.D.</td></tr>
<tr><td>Lecture(s)</td><td colspan="6">RNDr. Karel Škoch, Ph.D.</td></tr>
<tr><td>Syllabus</td><td colspan="6"></td></tr>
</table>

During a 2-week practical course, students will be introduced to the preparation, manipulation and characterization of air- and temperature-sensitive compounds by using synthesis in the glovebox and Schlenk technique. They will be trained in purifying solvents for sensitive transformations, working with argon/vacuum manifold, using Schlenk flasks, operating glovebox, performing filtration, distillation, sublimation and/or crystallization under strict inert atmosphere, preparing samples and making routine characterizations of prepared products.

The laboratory will be carried out at the Institute of Inorganic Chemistry (IIC), Czech Academy of Science. The practical content listed below is just a guideline for the possible work to the done – laboratory tasks will be updated annually according to the latest trends and challenges. Practicals will also reflect the student's research topic with an emphasis on individualization.

Motivation
Organic synthesis is an important tool in modern science and industry. It enables the preparation of various compounds like pharmaceuticals, functional materials, agrochemicals etc. The laboratory will focus on advanced techniques of preparation and isolation of reactive compounds. Students will learn advanced laboratory techniques of how to isolate reaction products in a controlled environment. The goal is to deepen skills and gain experience with a modern glovebox and Schlenk-line synthesis.

Objectives
The main goal is to introduce students to the advanced techniques of organic synthesis, and expand their experience with glovebox, Schlenk line and manipulating air-sensitive molecules. Firstly, students will learn how to operate argon-filled glovebox, prepare and handle Schlenk glassware, how to dry solvents from residual moisture and other impurities and how to set up a chemical reaction with strict exclusion of air. Furthermore, they will get experience with general purification methods such as cannula filtration, distillation and sublimation under controlled conditions and isolation and characterization of reaction products.

The specific set of reactions will be customized to the previous synthetic experience of students. Anticipated topics include the preparation and isolation of free N-heterocyclic carbene, transition metal-catalysed reactions (Suzuki-Miyaura cross-coupling), manipulation of organometallic reagents (such as butyllithium) and the synthesis of boron-containing cationic compounds.

An important aspect of the practical will be the isolation and characterization of prepared compounds, particularly by using multinuclear Nuclear Magnetic Resonance (NMR). Students will acquire experience in the preparation and measurement of samples sensitive to the atmosphere and further enhance their NMR skills.

The IIC is equipped with argon-filled glovebox Inert PURE-Lab, several Schlenk-lines and all necessary equipment. Characterization of prepared compounds will be performed primarily on JEOL 600 NMR spectrometer.

Acquired skills
During the course, students will gain proficiency in handling air-sensitive molecules, and mastering the operation of a glovebox and Schlenk line. They will learn to adeptly prepare and conduct reactions involving sensitive substances (such as free carbenes, organolithium reagents etc.), expanding their expertise in maintaining controlled environments.

Furthermore, students will develop the ability to characterize compounds by using advanced techniques like multinuclear NMR, enabling them to elucidate complex molecular structures. This hands-on experience will empower them to confidently navigate challenges associated with sensitive compounds and controlled atmospheres, preparing them for success in intricate organic synthesis endeavours.

Literature

1. J. R. Mohrig, D. G. Alberg, G. E. Hofmeister, P. F. Schatz, C. N. Hammond, *Laboratory Techniques in Organic Chemistry*, 4th Ed., W. H. Freeman and Company, (2014).
2. D. W. Rankin, N. W. Mitzel, C. A. Morrison, *Structural Methods in Molecular Inorganic Chemistry*, Wiley, (2013).
3. A. M. Borys, An Illustrated guide to Schlenk line techniques. *Organometallics* **42** (2023) 182.

B-III – Course details

Course title	**Laboratory VII – Biomedical and immunology testing**				
Type	C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)			**Recommended year**	1-3
Course length	40l	**Hours**	40	**Credits**	20
Course completion	Pre-exam credit			**Teaching type**	laboratory
Verification	Laboratory protocols				
Guarantor	**RNDr. Mgr. Ing. Petr Kelbich, Ph.D.**				
Lecture(s)	RNDr. Mgr. Ing. Petr Kelbich, Ph.D.				
Syllabus					

Motivation
The Institute of Biomedicine and Laboratory Diagnostics of the Faculty of Health Studies of J. E. Purkyne University and Masaryk Hospital in Ústí nad Labem includes the Department of Clinical Biochemistry, the Department of Laboratory Immunology and the Biomedical Centre. The modern equipment of all these departments provides a wide range of possibilities for studying the influence of various environmental factors, implants, new biomedical materials and their surfaces on the human organism.

Objectives
The Department of Clinical Biochemistry allows monitoring of many parameters in various body fluids, especially blood and urine. An example is the study of the influence of stress hormone levels on the level of biochemical parameters of homeostasis. The laboratory can provide expert and technical support for various topics. However, the relevant steps are always performed after they have been specified.

The Department of Laboratory Immunology provides a wide portfolio of measurements of various immunological parameters. The expected topics of study are the influence of environmental conditions on the manifestations of allergic, autoimmune or lymphoproliferative diseases. Details will also be addressed in accordance with the dissertation assignment.

The Biomedical Centre specializes in the analysis of various extravascular body fluids, including cerebrospinal fluid, intraocular fluid, pleural effusions, abdominal effusions, pericardial effusions, peritoneal fluid, synovial fluid, etc.

The Institute of Biomedicine and Laboratory Diagnostics in cooperation with the Clinic of Neurosurgery of the Faculty of Health Studies of J. E. Purkinje University and Masaryk Hospital in Ústí nad Labem enables studies focused on the detection of titanium in body fluids of patients with titanium implants and testing its toxicity. Another possibility is to study the application of nanomaterials on the surface structures of implants.

The detail laboratory tests and practical exercises will be specified based on students needs, more specifically, related to the topic of dissertation thesis.

Acquired skills and knowledge
After finishing the course, students will be familiar with immunological and/or biomedical testing relevant to their research topic. They should understand the relationship and correlation between materials, devices, technologies etc. being developed and their consequent testing in clinical and biomedical environments. Thus, they should have gained proficiency in designing biomaterials by already considering their future use in the medical environment. Students should also become familiar with medical terminology, therefore, being able to faster transfer laboratory examples into clinical studies. Students will become familiar with a biohazard working environment.

Literature

1. B. Alberts, R. Heald, K. Hopkin, A. Johnson, D. Morgan, K. Roberts, P. Walter. *Essential Cell Biology*, WW Norton & Company, (2023).
2. A. K. Abbas, A. H. Lichtman, S. Pillai. *Basic Immunology*, 7^{th} Ed., Elsevier, (2023).
3. D. Male, R. S. Peebles, V. Male, *Immunology*, 9^{th} Ed., Elsevier, (2020).
4. P. J. Delves, S. J. Martin, D. R. Burton, I. M. Roitt, *Roitt's Essential Immunology (Essentials)*, 13^{th} Ed., Wiley-Blackwell, (2016).

5. P. J. Kennelly, K. M. Botham, O. McGuinness, V. W. Rodwell, P. A. Weil, *Harper's Illustrated Biochemistry*, 32nd Ed., McGraw Hill/Medical, (2000).

B-III – Course details

Course title	**Laboratory VIII – Application-oriented testing of materials**				
Type	C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)			**Recommended year**	1-2
Course length	40l	**Hours**	40	**Credits**	20
Course completion	Pre-exam credit			**Teaching type**	laboratory
Verification	Oral				
Guarantor	**Dr. Ing. Birgit Jost**				
Lecture(s)	Dr. Ing. Birgit Jost				
Syllabus					

Motivation

The laboratory of the application-oriented characterization of materials will be carried out at the Fraunhofer Institute for Ceramic Technologies and Systems IKTS, Dresden. The laboratory will teach students a different approach to materials characterization. Nanoscale properties of materials control the macroscopic performance and reliability of different components, functions and processes. Novel and complex materials (systems) are therefore a key for innovations in micro-, nano- and optoelectronics, energy, environmental and medical (technology). Having the right knowledge about the relevant structure-property relationships can accelerate the development of new products, specifically improve components' reliability and increase technological processes' efficiency. This requires a deep understanding of materials and their time-resolved interactions from the atomic to the real size length-scale. The laboratory located at IKTS offers a unique infrastructure of high-resolution electron, ion and X-ray microscopy to provide competent consulting, contract analysis and methodological developments to partners in industry and research. A special focus is on the combination and correlation of different methods as well as the customized development of unique testing technology. As such, students will learn fast, reliable, and reproducible materials characterization which can support different industries.

Objectives

The aim of the course is to learn and understand complementary characterization techniques based on e-beam and X-ray sources. Students will predominantly learn *in-situ* analysis of different samples with a focus on nanometre length-scale characterization. Students will become familiar with different sample preparation methods, data collection and their interpretation. They should understand, for example, the failure mechanism of different materials in different applications, be able to characterize different deterioration modes of materials, and be able to interpret the complex complementary results.

The practical course will cover the following topics.

1. Imaging real-life components by scanning-electron microscopy (SEM) – Figure 1.
   - Sample preparation outside SEM and for analysis in other microscopes (inside SEM), different sample preparation between Ga-FIB and Plasma-FIB (FIB – focused-ion beam),
   - Sample characterization and how to interpret collected data,
   - *In-situ* testing tools – why do we use *in-situ* testing and what types of "small" testing can be done inside SEM? This will involve nanoindentation testing, and imaging samples *in-situ* under tensile and bending deformation,

Fig. 1. Different SEM techniques to be used by students during the practical course – *left*: Zeiss NVision 40 with Gallium-FIB; and *right*: Helios 5 PFIB Cxe with Plasma-FIB.

2. Imaging components by transmission-electron microscopy (TEM) – Figure 2.
   - Practising different imaging modes on samples prepared early in the aforementioned stage 1,
   - Interpretation of collected data, their analysis and comparison with SEM,
   - Students will also learn in-situ testing modes available such as *in-situ* heating, indentation, imaging samples under tensile load, and electrical testing of materials.

Fig. 2. Zeiss Libra 200 TEM to be used for the practical course and the *in-situ* testing.

3. X-ray tomography, µXCT and nXCT – Figure 3.
   - Description of the main parts of an X-Ray-Microscope,
   - Different imaging modes,
   - Analysis of samples prepared earlier in SEM,
   - Sample characterization: how to interpret and analyse the 2-D pictures obtained?,
   - Topographies: performing 3-D experiments, segmentation and interpretation of data,
   - *In-situ* testing tools: why do we use *in-situ* testing tools? Which small experiments can we do inside the microscope? Difference in experimental design in X-ray microscopy compared to electron microscopy.

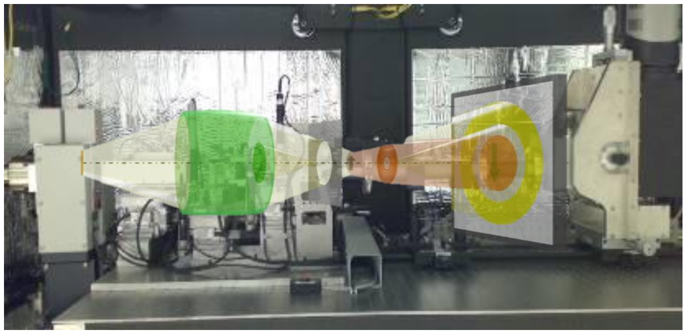

Fig. 3. Xradia nanoXCT-100 (now Carl Zeiss Ultra).

Acquired skills and knowledge

Students will gain skills SEM, TEM and XCT imaging of real-life components. Students will be able to prepare samples with the regions of interest for imaging. They should be able to plan the sample preparation in such a way that defects, sample deterioration etc. can be imaged and studied by various complementary techniques and methods. They will understand the benefits and limitations of each technique and should be able to suggest the best characterization method with respect to the material and defect of interest.

Literature

1. R. F. Egerton, *Physical Principles of Electron Microscopy*, Springer, (2018).
2. A. Weidner, R. Lehnert, H. Bierman, Scanning Electron Microscopy and Complementary In Situ Characterization Techniques for Characterization of Deformation and Damage Processes, in: *Austenitic TRIP/TWIP Steels and Steel-Zirconia Composites*, Springer, (2020). Available online at https://link.springer.com/book/10.1007/978-3-030-42603-3
3. H. Toda, *X-ray CT*, Springer, (2021).

<table>
<tr><th colspan="6">B-III – Course details</th></tr>
<tr><td>Course title</td><td colspan="5">Laboratory IX – Computational modelling of particle materials and fluid dynamics</td></tr>
<tr><td>Type</td><td colspan="3">C. Povinně volitelné praktické kurzy (Specialized laboratories and practicals)</td><td>Recommended year</td><td>1-2</td></tr>
<tr><td>Course length</td><td>22l</td><td>Hours</td><td>22</td><td>Credits</td><td>20</td></tr>
<tr><td>Course completion</td><td colspan="3">Pre-exam credit, exam</td><td>Teaching type</td><td>laboratory</td></tr>
<tr><td>Verification</td><td colspan="5">Laboratory protocols
Oral exam</td></tr>
<tr><td>Guarantor</td><td colspan="5">doc. Ing. Jaromír Havlica, Ph.D.</td></tr>
<tr><td>Lecture(s)</td><td colspan="5">doc. Ing. Jaromír Havlica, Ph.D.</td></tr>
<tr><td>Syllabus</td><td colspan="5"></td></tr>
</table>

Motivation

This practical modelling course is designed to provide doctoral students with a comprehensive understanding of modelling and simulation techniques for studying and predicting the behaviour and properties of powder and granular materials, fluids, and suspensions.

Objectives

The course will cover three main areas of modelling: i) the discrete element method (DEM) for powders and granular materials; ii) computational fluid dynamics (CFD) for aerodynamics and hydrodynamics; and iii) the modelling of suspensions by combining CFD and DEM.

Acquired skills and knowledge

Through practical examples, readings, and hands-on assignments, students will develop the skills needed to model and analyse complex systems at various scales.

1. *Concepts of computational modelling*: an overview of computational modelling techniques, basic concepts, and applications in particle materials and fluid dynamics.
2. *Discrete element method (DEM)*: fundamentals of DEM, particle interaction models, time integration schemes, parallelization strategies, and applications in powder and granular material simulations.
3. *Computational fluid dynamics (CFD)*: governing equations for fluid flow, numerical methods for solving fluid flow problems, turbulence modelling, boundary conditions, and applications in aerodynamics and hydrodynamics.
4. *Coupling DEM and CFD*: basics of coupling DEM and CFD for modelling particle-fluid interactions, algorithms for two-way coupling, and applications in suspension and multiphase flow simulations.
5. *Modelling of suspensions*: particle-fluid interaction forces, drag models, lift forces, virtual mass forces, and applications in simulating suspensions.
6. *Boundary conditions and mesh generation*: techniques for creating appropriate boundary conditions and mesh generation for complex geometries in both DEM and CFD simulations.
7. *Simulation software and programming*: Working with popular DEM and CFD software packages, writing custom code for specific problems, and parallelization techniques for high-performance computing.
8. *Model validation and verification*: techniques for validating and verifying computational models, comparing simulation results with experimental data, and assessing model accuracy and limitations.
9. *Advanced topics in DEM and CFD*: recent developments and research trends in DEM and CFD, including multiscale modelling, adaptive mesh refinement, and machine learning-assisted modelling.
10. *Applications and case studies*: practical applications and case studies of computational modelling in various industries, such as pharmaceuticals, food processing, energy, and materials science.
11. *Hands-on assignments and projects*: students will complete hands-on assignments and projects throughout the course, applying the concepts and techniques learned to real-world problems and simulations.

Literature	

1. S. Jayanti, *Computational Fluid Dynamics for Engineers and Scientists*, Springer, (2018).
2. C. R. Maliska, *Fundamentals of Computational Fluid Dynamics - The Finite Volume Method*, Springer International Publishing, (2023).
3. J. H. Ferziger, M. Perić, R. L. Street, *Computational Methods for Fluid Dynamics*, Springer International Publishing, (2019).
4. T. Pöschel, T. Schwager, *Computational Granular Dynamics: Models and Algorithms*, Springer-Verlag, (2005).
5. F. Radjai, F. Dubois, *Discrete-Element Modeling of Granular Materials*, Wiley, (2011).
6. D. Gelnar, J. Zegzulka, *Discrete Element Method in the Design of Transport Systems Verification and Validation of 3D Models*, Springer International Publishing, (2019).
7. W.-H. Zhou, Z.-Y. Yin, *Practice of Discrete Element Method in Soil-Structure Interface Modelling*, Springer Nature Singapore, (2022).
8. X. Wang, B. Li, R. Xia, H. Ma, *Engineering Applications of Discrete Element Method*, *Springer Nature Singapore*, (2020).