

RAČUNALNIŠKA DINAMIKA TEKOČIN

UČNI NAČRT PREDMETA/COURSE SYLLABUS

Predmet:	Računalniška dinamika tekočin
Course title:	Computational Fluid Dynamics
Članica nosilka/UL Member:	UL FS

Študijski programi in stopnja	Študijska smer	Letnik	Semestri	Izbirnost
Strojništvo - Razvojno raziskovalni program, druga stopnja, magistrski	Procesno strojništvo (smer)	1. letnik	2. semester	obvezni

Univerzitetna koda predmeta/University course code:	0566920
Koda učne enote na članici/UL Member course code:	6018-M

Predavanja /Lectures	Seminar /Seminar	Vaje /Tutorials	Klinične vaje /Clinical tutorials	Druge oblike študija /Other forms of study	Samostojno delo /Individual student work	ECTS
30		30			65	5

Nosilec predmeta/Lecturer:	doc. dr. Boštjan Mavrič, prof. dr. Božidar Šarler
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Izvajalci predavanj:	
Izvajalci seminarjev:	
Izvajalci vaj:	
Izvajalci kliničnih vaj:	
Izvajalci drugih oblik:	
Izvajalci praktičnega usposabljanja:	

Vrsta predmeta/Course type:	Obvezni strokovni predmet na smeri Procesno strojništvo, ki je izbirni strokovni predmet na ostalih smereh./Compulsory specialised course in the study of Process Engineering, which is an elective specialised course in other fields of study.
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Jeziki/Languages:	Predavanja/Lectures:	Slovenščina
	Vaje/Tutorial:	Slovenščina

Pogoji za vključitev v delo oz. za opravljanje študijskih obveznosti:

Prerequisites:

Izpolnjevanje pogojev za vpis v Magistrski študijski program II. stopnje Strojništvo - Razvojno raziskovalni program.	Meeting the enrollment conditions for the Master's study programme of Mechanical Engineering - Research and Development program.
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Vsebina:

Content (Syllabus outline):

- Uvod: - cilji in namen predmeta, predstavitev učnega programa, študijskih pripomočkov in virov, - predstavitev obveznosti študentov in napotki za uspešen študij, - pomen računalniške dinamike tekočin v tehniki. - Pregled vodilnih enačb, ki jih obravnavamo v okviru računalniške dinamike tekočin ter njihove specifičnosti s strani numerične obravnave: - potencialni, neviskozni, viskozni tok, Stokesov, Burgersov, Navier-Stokesov tok, - podzvočni-nadzvočni, laminarni-turbulentni tok, - tok brez in z kemijskimi reakcijami, enofazni-večfazni tok. - Elementi računalniške dinamike tekočin: - struktura simulacijskega sistema: priprava vhodnih podatkov, rešitveni postopek, priprava in analiza izhodnih podatkov, - strojna oprema za računalniško dinamiko tekočin: vektorska, vzporedna, grafična, v oblaku. - Obravnava specifik nekaterih komercialnih programov: CFX, ANSYS FLUENT, STARCCM,... in odprtokodnih programov: Gerris, OpenFOAM,... - Zasnove rešitvenih postopkov enačb dinamike tekočin: - metoda utežnih ostankov in izpeljanke: metoda končnih razlik, metoda kontrolnih volumnov, metoda končnih elementov, metoda robnih elementov, brez mrežne metode, - hidrodinamika gladkih delcev, - mrežno-Boltzmannove metode. - Krajevna diskretizacija skalarnih in vektorskih polj dinamike tekočin: - oblikovne in utežne funkcije: polinomi, radialne bazne funkcije, Chebyshevi polinomi, itd. - izračun koeficientov oblikovnih in utežnih funkcij: različne vrste kolokacij in izpeljank metode najmanjših kvadratov, - primeri in demonstracije računalniškega programa. - Časovna diskretizacija skalarnih in vektorskih polj dinamike tekočin: - dvonivojske metode: eksplisitna metoda, implicitna metoda, Crank-Nicolsonova metoda, - večnivojske metode, - primeri in demonstracija računalniškega programa. - Metoda kontrolnih volumnov za ustaljene difuzijske probleme: - krajevna diskretizacija drugega in višjih redov, - v eni in več dimenzijah, - primeri in demonstracija računalniškega programa. - Metoda kontrolnih volumnov za ustaljene konveksijsko-difuzijske probleme: - konzervativnost, transportivnost, omejenost, - privetrne sheme prvega in drugega reda, sheme z omejevalci, - primeri in demonstracija računalniškega programa. - Sklopitev hitrosti in tlaka v metodi kontrolnih volumnov	- Introduction: - objectives and purpose of the subject, presentation of the syllabus, study aids and resources, - presentation of student obligations, and directions for successful study, - importance of computational fluid dynamics in engineering. - Overview of the governing equations which are tackled in the framework of computational fluid dynamics and their specifics from the numerical point of view: - potential, nonviscous, viscous flow, Stokes, Burgers, Navier-Stokes flow, - subsonic-supersonic, laminar-turbulent flow, - flow with and without chemical reactions, single-phase, multi-phase flow. - Elements of computational fluid dynamics: - structure of simulation system: preparation of input data, solution procedure, preparation and analysis of output data, - hardware equipment for computational fluid dynamics: vectorial, parallel, graphic, in the cloud. - Discussion of specifics of some commercial codes: CFX, ANSYS FLUENT, STARCCM, ... and open-source codes: Gerris, OpenFOAM,... - Basis of solution procedures of fluid dynamics equations: - method of weighted residuals and variants: finite difference method, finite volume method, finite element method, boundary element method, meshless methods, - smooth particle hydrodynamics, - Boltzmann mesh methods. - Krajevna diskretizacija skalarnih in vektorskih polj dinamike tekočin: - shape and weighting functions: polynomials, radial basis functions, Chebyshev polynomials, etc. - calculation of coefficients of weight functions: different types of collocation and variants of least squares method, - examples and demonstration of computer code. - Time discretisation of scalar and vector fields of fluid dynamics: - two-level schemes: explicit method, implicit method, Crank-Nicolson method, - multilevel schemes, - examples and demonstration of computer code. - Finite volume method for steady diffusion problems: - space discretisation of the second and higher levels, - in one and multiple dimensions, - examples and demonstration of computer code. - Finite volume method for steady convection-diffusion problems: - conservation, transportivity, boundedness, - upwinding schemes of first and second order, schemes with limiters,
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- zamaknjena in nezamaknjena mreža - SIMPLE algoritem in izpeljanke za nestisljivi in stisljivi tok - primeri in demonstracija računalniških programov. 10. Specifika izračuna sistemov enačb računalniške dinamike tekočin: - direktne metode: uporaba TDMA algoritma v eni in več dimenzijah ter za sheme drugega in višjih redov, - iterativne metode in relaksacijske metode, - večmrežne iterativne metode. 11. Metoda kontrolnih prostornin za neustaljene probleme: - konvekcijsko-difuzijski problem, - Navier-Stokesove enačbe, - struktura sklopitve različnih skalarnih in vektorskih enačb. 12. Numerična implementacija robnih pogojev: - robni pogoji za temperaturo, tlak, hitrost, koncentracijo, - togo-stenski, vstopni in izstopni robni pogoji, - simetrični in ciklični robni pogoji. 13. Napake in nedoločenosti pri računalniški dinamiki tekočin: - napake vstopnih podatkov in numerične napake, Richardsonova ocena napake - verifikacija in validacija - napotki za pravilno uporabo računalniške dinamike tekočin. 14. Sklopitev simulacij računalniške dinamike tekočin z drugimi simulacijami: - sklopitev z dinamiko trdnin in elektromagnetnim poljem - sklopitev z metodmi umetne inteligence, - razvoj časovno povezanih simulacij iz časovno nepovezanih simulacij. 15. Specifike simulacije zapletenih sistemov z računalniško dinamiko tekočin: - sevanje, - večsestavinski in večfazni sistemi, - zgorevanje.	- examples and demonstration of computer code. 9. Coupling of velocity and pressure in finite volume method - staggered and non-staggered grid, - SIMPLE algorithm and variants for incompressible and compressible flow, - examples and demonstration of computer codes. 10. Specifics of computation of systems of equations in computational fluid dynamics: - direct methods: use of TDMA algorithm in one and multiple dimensions and for schemes of second and higher orders, - iterative methods and relaxation methods, - multigrid iterative methods. 11. Finite volume method for transient problems: - convection-diffusion problems, - Navier-Stokes equations, - structure of coupling of different scalar and vector equations. 12. Numerical implementation of boundary conditions: - boundary conditions for temperature, pressure, velocity, concentration, - solid wall, inlet and outlet boundary conditions, - symmetry and cyclic boundary conditions. 13. Errors and uncertainty in computational fluid dynamics: - errors in input data and numerical errors, Richardson's error estimation, - verification and validation, - guidances for proper use of computational fluid dynamics. 14. Coupling of computational fluid dynamics simulations with other simulations: - coupling with solid dynamics and electromagnetic field, - coupling with artificial intelligence methods, - development of on-line simulations from off-line simulations. 15. Specifics of simulation of complicated systems with computational fluid dynamics: - radiation, - multiconstituent and multiphase systems, - combustion.
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Temeljna literatura in viri/Readings:

1. F. Moukalled, L. Mangani, M. Darwish, The Finite Volume Method in Computational Fluid Dynamics: An Advanced Introduction with OpenFOAM and Matlab, Springer Verlag, Cham, 2016. ISBN - 978-3-319-16873-9, [COBISS.SI-ID [16741403](#)]
2. H. K. Versteeg, W. Malalasekera, An Introduction to Computational Fluid Dynamics, The Finite Volume Method, 2nd Edition, Pearson, Harlow, 2007. ISBN - 0-582-21884-5, [COBISS.SI-ID [279547](#)]
3. G.R. Liu, Mesh Free Methods: Moving Beyond Finite Element Method, CRC Press, Boca Raton, 2nd Edition, 2003. ISBN - 0-8493-1238-8, [COBISS.SI-ID [418537](#)]

Cilji in kompetence:

Objectives and competences:

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Cilji: 1. Seznaniti študente z osnovnimi načeli računalniških programov za simulacijo toka tekočine (kapljevine in plini), ki jih spremljajo različni drugi pojavi (prenos toplote, prenos sestavin, mehanika trdnin, elektromagnetno polje), zapisani na osnovi ustreznih parcialnih diferencialnih enačb (PDE). 2. Študente naučiti poglobljene uporabe vsaj enega programa za računalniško dinamiko tekočin (RDT). 3. Navdušiti študente za RDT in jih spodbuditi k podrobnejšemu preučevanju predstavljenih osnov. Kompetence: 1. Razumeti osnovna načela in strukturo simulacijskih sistemov za RDT. (S1-MAG) 2. Razumeti probleme diskretizacije: konsistentnost, stabilnost, konvergenco, red diskretizacije, numerično difuzijo, ... (S1-MAG, P1-MAG) 3. Zavedati se posebnosti pri reševanju Navier-Stokesovih enačb in problemov numeričnega modeliranja turbulentnega toka. (P4-MAG) 4. Znati izbrati ustrezno formulacijo in numerični pristop za obravnavani fizikalni problem in ustrezno preveriti dobljene rezultate. (S8-MAG, S10-MAG)	Objectives: 1. To acquaint students with the basic principles of computer programs for fluid flow simulation (liquids and gases), accompanied by various other phenomena (heat transfer, species transfer, solid mechanics, electromagnetic field), written on the basis of appropriate partial differential equations (PDE). 2. Teach students the in-depth use of at least one computational fluid dynamics (CFD) program. 3. To inspire students for CFD and encourage them to study the presented fundamentals in more detail. Competences: 1. Understand the basic principles and structure of simulation systems for CFD. (S1-MAG) 2. Understand discretization problems: consistency, stability, convergence, discretization order, numerical diffusion, ... (S1-MAG, P1-MAG) 3. To be aware of the peculiarities of solving the Navier-Stokes equations and the problems regarding numerical modeling of turbulent flow. (P4-MAG) 4. Being able to choose the appropriate formulation and numerical approach for the given physical problem and to check the obtained results. (S8-MAG, S10-MAG)
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Predvideni študijski rezultati: Znanja: Poznati različne metode diskretizacij PDE; poudarek je na metodi kontrolnih volumnov, ki prevladuje v najbolj razširjenih programih za RDT. Biti sposoben smiselne in učinkovite uporabe simulacijskih sistemov za RDT ter kritične ocene izračunanih rezultatov. Poglobljeno teoretično, metodološko in analitično znanje z elementi raziskovanja, ki je osnova za zelo zahtevno strokovno delo, Z2. Spretnosti: Poglobljeno obvladati vsaj simulacijski sistem (komercialni ali odprtokodni) za RDT. S2.1	Intended learning outcomes: Knowledge: Know different PDE discretization methods; the emphasis is on the control volume method, which is prevalent in the most widely used CFD programs. Be able to make meaningful and effective use of CFD simulation systems and to critically evaluate calculated results. Thorough theoretical, methodological and analytical knowledge with elements of a research work that form a basis for very demanding professional work, Z2. Skills: To master at least one simulation system (commercial or open source) for CFD. S2.1
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Metode poučevanja in učenja:

Learning and teaching methods:

P1: Avditorna predavanja z reševanjem izbranih - za področje značilnih - teoretičnih in praktično uporabnih primerov.. P14: Občasna uporaba računalniške animacije. P5: Uporaba študijskega gradiva v obliki (učbenik predavanj). P6: Demonstracija računalniške kode. P3: Avditorialne vaje – teroetično znanje podkrepjeno z računskimi primeri. P5: Uporaba študijskega gradiva v obliki (učbenik za vaje). P4: Laboratorijske vaje: praktično delo s simulacijskim sistemom za RDT.	P1: Auditorial lectures with solving selected field-specific theoretical and applied use cases. P14: Occasional use of computer animation. P5: Application of study material (textbook for lectures). P6: Demonstration of computer code. P3: Auditorial exrecises, in which theoretical content from the lectures is supplemented with practical examples. P5: Application of study material (textbook for exercises). P4: Laboratory exercises: on hands work with simulation system for CFD.
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Načini ocenjevanja:	Delež/Weight	Assessment:
Pisni izpit	50,00 %	Written exam
Izdelan RDT projekt	50,00 %	Accomplished CFD project

Ocenjevalna lestvica:	Grading system:
5 - 10, pri čemer velja, da je pozitivna ocena od 6 - 10	5 - 10, a student passes the exam if he is graded from 6 to 10

Reference nosilca/Lecturer's references:

Božidar Šarler:

1. DOBRAVEC, Tadej, MAVRIČ, Boštjan, **ŠARLER, Božidar**. Acceleration of RBF-FD meshless phase-field modelling of dendritic solidification by space-time adaptive approach. *Computers & mathematics with applications*. Nov. 2022, vol. 126, str. 77-99, ilustr. ISSN 1873-7668. <https://www.sciencedirect.com/science/article/pii/S0898122122003881>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=141046>, DOI: 10.1016/j.camwa.2022.09.008. [COBISS.SI-ID 122502403]
2. REK, Zlatko, **ŠARLER, Božidar**. Formulation of the method of fundamental solutions for two-phase Stokes flow. *Engineering analysis with boundary elements*. Jan. 2024, vol. 158, str. 199-210, ilustr. ISSN 0955-7997. <https://www.sciencedirect.com/science/article/pii/S0955799723005167>, <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=152128>, DOI: 10.1016/j.enganabound.2023.10.024. [COBISS.SI-ID 171090179]
3. ZAMOLO, Riccardo, NOBILE, Enrico, **ŠARLER, Božidar**. Novel multilevel techniques for convergence acceleration in the solution of systems of equations arising from RBF-FD meshless discretizations. *Journal of computational physics*. 2019, vol. 392, str. 311-334, ilustr. ISSN 0021-9991. <https://www.sciencedirect.com/science/article/pii/S0021999119303171>. [COBISS.SI-ID 16607003] Ref 3
4. VERTNIK, Robert, MRAMOR, Katarina, **ŠARLER, Božidar**. Solution of three-dimensional temperature and turbulent velocity field in continuously cast steel billets with electromagnetic stirring by a meshless method. *Engineering analysis with boundary elements*. [Print ed.]. Jul. 2019, vol. 104, str. 347-363, ilustr. ISSN 0955-7997. <https://www.sciencedirect.com/science/article/pii/S0955799718305010?via%3Dihub>, DOI: 10.1016/j.enganabound.2019.03.026. [COBISS.SI-ID 1474474]
5. HATIĆ, Vanja, CISTERNAS FERNÁNDEZ, Martín, MAVRIČ, Boštjan, ZALOŽNIK, Miha, COMBEAU, Hervé, **ŠARLER, Božidar**. Simulation of a macrosegregation benchmark in a cylindrical

coordinate system with a meshless method. International journal of thermal sciences. Aug. 2019, vol. 142, str. 121-133, ilustr. ISSN 1290-0729.
<https://www.sciencedirect.com/science/article/pii/S1290072918319197>, DOI: 10.1016/j.ijthermalsci.2019.04.009. [COBISS.SI-ID [1476266](#)]

Boštjan Mavrič:

1. ANA, Khush Bakhat, **MAVRIČ, Boštjan**, ZAHOOOR, Rizwan, ŠARLER, Božidar. A meshless solution of the compressible viscous flow in axisymmetric tubes with varying cross-sections. *Engineering analysis with boundary elements*. Oct. 2022, vol. 143, str. 340-352, ilustr. ISSN 0955-7997.
<https://www.sciencedirect.com/science/article/pii/S0955799722002260>, [Repozitorij Univerze v Ljubljani – RUL](#), DOI: [10.1016/j.enganabound.2022.06.029](#). [COBISS.SI-ID [114950915](#)],
2. NAJAFI, Mahboubeh, DEHGHAN, Mehdi, ŠARLER, Božidar, KOSEC, Gregor, **MAVRIČ, Boštjan**. Divergence-free meshless local Petrov–Galerkin method for Stokes flow. *Engineering with computers*. [Online ed.]. Dec. 2022, vol. 38, iss. 6, str. 5359-5377. ISSN 1435-5663.
<https://link.springer.com/article/10.1007/s00366-022-01621-w>, DOI: [10.1007/s00366-022-01621-w](#). [COBISS.SI-ID [99503875](#)],
3. **MAVRIČ, Boštjan**, DOBRAVEC, Tadej, ŠARLER, Božidar. Lessons from accelerating an RBF-FD phase-field model of dendritic growth on GPUs. V: ŠARLER, Božidar (ur.), VANOLI, Laura (ur.), DOBRAVEC, Tadej (ur.). *Eurotherm 2024 : 9th European Thermal Sciences Conference, 10/06/2024 - 13/06/2024, Lake Bled, Slovenia*. [S. l.]: IOP publishing, 2024. Vol. 2766, [article no.] 012168, str. 1-6, ilustr. Journal of physics. Conference series (Online), vol. 2766. ISSN 1742-6596.
<https://iopscience.iop.org/article/10.1088/1742-6596/2766/1/012168>, [DiRROS - Digitalni repozitorij raziskovalnih organizacij Slovenije](#), DOI: [10.1088/1742-6596/2766/1/012168](#). [COBISS.SI-ID [208869891](#)],
4. LARSSON, Elisabeth, **MAVRIČ, Boštjan**, MICHAEL, Andreas, POOLADI, Fatemeh, TOMINEC, Igor. Meshfree RBF–FD methods for numerical simulation of PDE problems. V: ŠARLER, Božidar (ur.), VANOLI, Laura (ur.), DOBRAVEC, Tadej (ur.). *Eurotherm 2024 : 9th European Thermal Sciences Conference, 10/06/2024 - 13/06/2024, Lake Bled, Slovenia*. [S. l.]: IOP publishing, 2024. Vol. 2766, [article no.] 012158, str. 1-6, ilustr. Journal of physics. Conference series (Online), vol. 2766. ISSN 1742-6596.
<https://iopscience.iop.org/article/10.1088/1742-6596/2766/1/012158>, [DiRROS - Digitalni repozitorij raziskovalnih organizacij Slovenije](#), DOI: [10.1088/1742-6596/2766/1/012158](#). [COBISS.SI-ID [208931075](#)],
5. **MAVRIČ, Boštjan**, DOBRAVEC, Tadej, ŠARLER, Božidar. Lessons from accelerating an RBF-FD phase-field model of dendritic growth on GPUs. V: ŠARLER, Božidar (ur.), VANOLI, Laura (ur.), DOBRAVEC, Tadej (ur.). *Eurotherm 2024 : 9th European Thermal Sciences Conference, 10/06/2024 - 13/06/2024, Lake Bled, Slovenia*. [S. l.]: IOP publishing, 2024. Vol. 2766, [article no.] 012168, str. 1-6, ilustr. Journal of physics. Conference series (Online), vol. 2766. ISSN 1742-6596.
<https://iopscience.iop.org/article/10.1088/1742-6596/2766/1/012168>, [DiRROS - Digitalni repozitorij raziskovalnih organizacij Slovenije](#), DOI: [10.1088/1742-6596/2766/1/012168](#). [COBISS.SI-ID [208869891](#)],