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Tutorial

PARTICLE-LADEN FLOWS DEMYSTIFIED: FROM SIMPLE TO COMPLEX PARTICLE MODELS

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ABSTRACT:

Particles in flows can sustain life, threaten it, and shape our future. From red blood cells transporting oxygen and bacteria spreading through fluids to airborne pollutants, volcanic ash, and cells cultivated in bioreactors for medicine and sustainable food production, particles play a fundamental role in numerous biological, environmental, and industrial processes. Despite their diversity, these systems share a common challenge: predicting the motion and interactions of enormous numbers of particles in fluid flows. Even at relatively low concentrations, particle numbers can reach millions or billions, making fully resolving each individual particle and its surrounding fluid flow computationally prohibitive. This motivates the development of efficient numerical modeling approaches capable of handling large particle populations. An additional challenge arises from the complex properties of real-world particles, which are rarely perfectly spherical, homogeneous, or rigid. Accurately predicting their motion, interactions, and deposition therefore requires numerical approaches that carefully balance physical realism with computational efficiency.

The Tutorial provides a structured and accessible introduction to the numerical modeling of particle-laden flows, with particular emphasis on the efficient simulation of large numbers of dilute, dispersed particles. Based on recent peer-reviewed journal publications and conference contributions, the Tutorial introduces the classical point-particle tracking framework and its systematic extensions toward more realistic non-spherical, inhomogeneous, colliding, and deformable particles.
Traditionally, numerical simulations often assume rigid, homogeneous, isolated spherical particles. While computationally efficient, these assumptions may limit predictive accuracy when particle shape, orientation, mass distribution, or deformability plays an important role. More advanced particle models can account for these effects, but introduce additional physical and numerical complexity.

The purpose of this Tutorial is to demystify numerical particle modeling by explaining the underlying physical concepts, fundamental assumptions, and practical limitations of different modeling approaches. The emphasis is on conceptual understanding and practical relevance rather than detailed mathematical derivations. Starting from the governing equations of particle motion and the fundamentals of Lagrangian particle tracking, the Tutorial progressively introduces more advanced models, including rigid non-spherical particles represented by superellipsoids, inhomogeneous particles, advanced collision models, and soft particles. Representative computational examples will illustrate how different levels of particle-model complexity influence particle trajectories, interactions, and deposition patterns.

The Tutorial aims to provide participants with a clear understanding of how to select an appropriate particle model for a given flow problem, when more advanced particle descriptions become necessary, and how to balance physical accuracy with computational cost when simulating large numbers of particles.

Jana Wedel received her PhD in Mechanical Engineering with distinction (Dr.-Ing., grade 1.0) from the Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany, in 2025. Her doctoral research focused on the numerical modeling of micro-particles in fluid flows, with particular emphasis on the behavior of both rigid and deformable particles in dilute multiphase systems. Her work addresses fundamental and applied problems in particle–fluid interactions, including aerosol transport and deposition in realistically modeled human lungs, the dynamics of non-spherical particles such as pollen and asbestos fibers, and the deformation and motion of soft microparticles relevant for nanodrug delivery applications. She conducts collaborative research with the University of Maribor, Faculty of Mechanical Engineering, where she has recently also been appointed as a Research Assistant.
Dr. Wedel has authored and co-authored more than 26 scientific publications in the fields of multiphase flow modeling, particle dynamics, computational fluid dynamics and bioheat modelling. Her research relies strongly on advanced numerical methods and open-source CFD tools, particularly OpenFOAM, which she has been working with since 2014. She first applied OpenFOAM during her dual study program at Schaeffler Technologies in collaboration with the Technische Hochschule Nürnberg Georg Simon Ohm, where she investigated cavitation and multiphase flows in rotating geometries relevant to engine systems.
In addition to her research activities, Dr. Wedel is actively involved in teaching and knowledge transfer. She has been teaching numerical fluid dynamics with OpenFOAM to master's students at Technische Hochschule Nürnberg since September 2020 and has provided specialized OpenFOAM training courses and consulting for industry professionals through her own business, Wedel Dynamics, since September 2022 in cooperation with Prof. Dr. Markus Schmidt (TH Nürnberg). Her work bridges academic research and industrial application, focusing on advanced CFD methods for complex multiphase and particle-laden flows. She is also internationally engaged through research collaborations and professional exchanges, including work in Vietnam with Schaeffler Technologies in 2017 and ongoing collaborations with the University of Maribor, involving frequent research exchanges since 2021.
Her contributions have been recognized with several prestigious awards and distinctions. In 2021, she received the Bayerischer Ingenieurinnenpreis, honoring outstanding achievements by women engineers in Bavaria, and in 2022, she won second place in the Best Presentation Award competition at the World Congress on Computational Mechanics (WCCM). In 2026, she received the GACM Best PhD Award, which recognizes the best doctoral thesis in computational mechanics in Germany. Selected by the German Association for Computational Mechanics (GACM) to represent Germany in the European ECCOMAS competition, she went on to receive the ECCOMAS PhD Award for her dissertation, Dancing with the Flows: Numerical Modeling of Non-Ideal Micro-Particles in Fluids. Her dissertation was completed under the supervision of Prof. Paul Steinmann (FAU) and Prof. Matjaž Hriberšek and Prof. Jure Ravnik (University of Maribor). In the same year, she was also selected as one of five finalists for the ERCOFTAC da Vinci Prize.

Jure Ravnik is a Slovenian physicist and mechanical engineer, born in 1973. He is a Full Professor at the Faculty of Mechanical Engineering, University of Maribor, and heads its Laboratory for Transport Phenomena in Solids and Fluids. He graduated in physics from the University of Ljubljana in 1997. He then earned an MSc in Environmental Engineering (2003) and a PhD in Mechanical Engineering (2006), both at the University of Maribor. Before his academic career he worked as a researcher at the Jožef Stefan Institute in Ljubljana and as an environmental engineer at the Ecological Engineering Institute in Maribor. He joined the Faculty of Mechanical Engineering in 2003 and rose from teaching assistant to assistant professor (2008), associate professor (2013) and full professor (2018). He has also held senior leadership roles. He headed the Mechanical Engineering Research Institute from 2018 to 2023. He led the Environmental Engineering study programmes since 2015, has sat on the University Senate since 2023, and has chaired the Faculty's Academic Assembly since 2024.
His research covers numerical modelling of transport phenomena: turbulence, multiphase and particle-laden flows, and heat and mass transfer. He has published 111 original scientific articles, cited more than 2,400 times, with an h-index of 28 on Google Scholar. He also wrote several research codes, among them the open-source meshless flow simulation Vreteno for Lagrangian particle tracking, and the open-source PetFlow. His early work developed fast boundary element methods for the Navier–Stokes equations, using matrix compression to make large 3D problems practical. He later coupled these solvers with uncertainty quantification and applied them to nanofluids, brain stimulation and electromagnetic–thermal dosimetry. A second main line of work is the dynamics of inertial and deformable particles. With partners at FAU Erlangen-Nürnberg and the University of Udine he derived lift-force models, tested the limits of Jeffery's theory in turbulence, and built a superellipsoidal framework for complex particle shapes, soft particles and data-driven surrogate models. During the COVID-19 pandemic his team studied aerosol deposition in human airways across age groups and from specific anatomies, which is now his most-cited recent work. He also works closely with industry and public agencies. He has written about 50 research reports, built freeze-drying models for the pharmaceutical company Lek and developed natural gas consumption profiles for the energy regulators of Slovenia and Croatia.
His work is recognised with the University of Maribor Award for excellence in research (2019), the University's Bronze Medal (2011), and a bronze award for industrial cooperation from the Chamber of Commerce and Industry of Slovenia (2020). Early in his career he held DAAD, Alpe-Adria and HPC-Europa fellowships and visited Erlangen, Udine, Stuttgart and the Wessex Institute of Technology. He has given 33 invited conference lectures and 18 invited talks at foreign universities in Europe and the United States.
He edits the journal Environmental Modeling & Assessment. He sits on the editorial boards of Engineering Analysis with Boundary Elements, Acta Mechanica and Energies, and reviews for more than 60 journals. He co-chaired the 12th International Conference on Advances in Fluid Mechanics (2018) and served on the scientific committee of EUROMECH Colloquium 652 (2020). He is active in ERCOFTAC, ECCOMAS and several COST Actions, and was General Secretary of the Slovenian Society for Mechanics.
As a teacher he covers fluid mechanics, heat and mass transfer, numerical methods and environmental modelling, and has written three university textbooks in Slovene. He has supervised or co-supervised eight completed PhD theses, and two more are in progress. He has also supervised a postdoctoral fellow, 20 MSc theses and 30 BSc theses.

Ivan Dominik Horvat is a Croatian mechanical engineer and researcher, born in 1995. He is currently a Research Assistant at the Faculty of Mechanical Engineering, University of Maribor, Slovenia. He obtained his Bachelor's degree in Mechanical Engineering from the University of Rijeka in 2017, followed by a Master's degree from the University of Maribor in 2021. He completed his doctoral studies in Mechanical Engineering at the University of Maribor, earning his PhD in 2026 under the supervision of Jurij Iljaž. He joined the Faculty of Mechanical Engineering in 2021 as a Young Researcher and has worked as a Research Assistant since 2025. Before entering academia, he gained industrial experience in engineering project management, precision machining, and technical documentation.
His research focuses on numerical modeling of heat transfer, computational bioheat transfer, inverse problems, and biomedical applications of electromagnetic–thermal interactions. His doctoral research concentrated on developing numerical methods for transient Fourier and non-Fourier heat transfer using the boundary element method (BEM). He applied these methods to modeling heat transfer in biological tissues and solving inverse problems related to dynamic infrared thermography for skin cancer diagnostics. His work contributes to the development of numerical approaches for understanding thermal processes in biological tissues and their potential applications in medical diagnostics.
His current research addresses coupled electromagnetic–thermal modeling of biological tissues exposed to wireless communication technologies. Within the Slovenian–Croatian bilateral research project HERWICT, he contributes to developing computational models for assessing electromagnetic energy absorption and the resulting thermal response of the human body. His work combines numerical simulations, anatomically realistic models, and experimental infrared thermography. He also investigates uncertainty quantification, sensitivity analysis, and computationally efficient approaches to bioheat modeling, with particular emphasis on numerical simulations using OpenFOAM.
He has authored or co-authored at least 11 scientific publications, including six journal articles, three book chapters, and two conference proceedings papers. His research has been published in international journals, including *Computer Methods in Applied Mechanics and Engineering*, *Engineering Analysis with Boundary Elements*, *Journal of Thermal Biology*, *Journal of Integral Equations and Applications*, and *Strojniški vestnik – Journal of Mechanical Engineering*. Beyond biomedical heat transfer, he has contributed to collaborative research on data-driven surrogate modeling of deformable particles in viscous flows. His research activities also involve international collaborations with researchers from Friedrich-Alexander-Universität Erlangen-Nürnberg and the University of Split.
His computational expertise includes scientific programming in Fortran, C++, Python, and MATLAB, with experience in numerical methods for partial differential equations, boundary element methods, inverse problem solving, and OpenFOAM-based simulations. His teaching experience began at the University of Rijeka, where he served as a Student Teaching Assistant in Mechanics–Dynamics (2016–2017) and Hydraulic Machines (2017). In 2026, he co-supervised a bachelor's thesis at the University of Maribor investigating the thermal effects of Bluetooth electromagnetic radiation on human tissue. During his undergraduate studies, he received scholarships for academic excellence from the Croatian National Foundation for Support of Pupil and Student Standards in 2016 and 2017.

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