Course guide
205365 - 205365 - Turbulence II: Advanced Simulation, Modelling and Aerodynamics

Last modified: 25/09/2026

Unit in charge: Terrassa School of Industrial, Aerospace and Audiovisual Engineering
Teaching unit: 724 - MMT - Department of Heat Engines.

Degree: MASTER'S DEGREE IN INDUSTRIAL ENGINEERING (Syllabus 2013). (Optional subject).
MASTER'S DEGREE IN AERONAUTICAL ENGINEERING (Syllabus 2014). (Optional subject).
MASTER'S DEGREE IN SPACE AND AERONAUTICAL ENGINEERING (Syllabus 2016). (Optional subject).
MASTER'S DEGREE IN MECHANICAL ENGINEERING RESEARCH (Syllabus 2024). (Optional subject).
MASTER'S DEGREE IN INDUSTRIAL ENGINEERING (Syllabus 2025). (Optional subject).

Academic year: 2026 **ECTS Credits:** 3.0 **Languages:** English

LECTURER

Coordinating lecturer: Trias Miquel, Francesc Xavier

Others:

TEACHING METHODOLOGY

The course is developed through lectures, practical sessions and supervised hands-on activities. Theoretical sessions are supported by slides, videos and examples from numerical simulations and turbulent-flow databases.
Practical sessions are devoted to the preparation and supervision of the assignments, including code explanation, numerical implementation, post-processing of results and discussion of difficulties encountered by the students.
At least two hands-on sessions are planned: one on the algebra-based Navier-Stokes solver and fractional-step method,and one on Burgers' equation, spectral solution and LES modelling.

LEARNING OBJECTIVES OF THE SUBJECT

The course provides an advanced view of the numerical simulation and modelling of turbulent flows, with emphasis on the discretization of the incompressible Navier-Stokes equations, pressure-velocity coupling, turbulence modelling and aerodynamic applications.
At the end of the course, students should be able to formulate and analyse discrete forms of the Navier-Stokes equations, understand projection methods for incompressible flows, assess numerical reliability and computational cost, and compare DNS, RANS, LES and hybrid modelling strategies for turbulent and aerodynamic flows.

STUDY LOAD

Type	Hours	Percentage
Hours large group	27,0	36.00
Self study	48,0	64.00

Total learning time: 75 h

CONTENTS

Module 1: From Navier-Stokes equations to discrete operators

Description:
Review of the incompressible Navier-Stokes equations from the perspective of numerical simulation.
Introduction to discrete differential operators and their role in preserving relevant mathematical and physical properties.
Discussion of inner products, gradient, divergence, Laplacian and convective operators, with emphasis on conservation, consistency and stability properties.

Related activities:
Exercise on the construction and interpretation of simple discrete operators.
Analysis of the relation between continuous and discrete gradient/divergence operators.
Short problem on conservation, symmetry or skew-symmetry properties of discrete operators.

Full-or-part-time: 12h 30m
Theory classes: 4h 30m
Self study : 8h

Module 2: Discretization of the Navier- Stokes equations

Description:
Finite-volume discretization of the incompressible Navier-Stokes equations.
Treatment of convective, diffusive and pressure-gradient terms. Discretization on structured and unstructured meshes. Role of boundary conditions, interpolation, numerical fluxes and local truncation errors. Discussion of consistency, conservation and numerical robustness in the discretization of
turbulent-flow equations.

Related activities:
Derivation of discrete approximations for selected terms in the Navier-Stokes equations.
Exercise on local truncation error or flux discretization.
Implementation or analysis of a simple discrete operator for a model convection- diffusion problem.

Full-or-part-time: 14h
Theory classes: 5h
Self study : 9h

Module 3: Pressure-velocity coupling and projection methods

Description:
Numerical treatment of incompressibility and pressure-velocity coupling.
Helmholtz-Hodge decomposition, fractional-step and projection methods.
Derivation of the pressure Poisson equation, velocity prediction and velocity correction steps.
Discussion of the computational cost of the Poisson problem
and its relevance in incompressible-flow simulations.

Related activities:
Exercise deriving the fractional-step algorithm for the incompressible Navier-Stokes equations. Analysis of the pressure Poisson equation and velocity correction step. Hands-on work related to Assignment 1: algebra-based Navier-Stokes solver and channel-flow simulation.

Full-or-part-time: 12h 30m
Theory classes: 4h 30m
Self study : 8h

Module 4: Verification, stability and computational aspects

Description:
Numerical reliability of CFD simulations. Sources of error: modelling, discretization, solver residual and round-off errors. Code verification, including the Method of Manufactured Solutions. Stability of time-integration schemes, CFL condition and spectral-radius interpretation. Brief introduction to computational cost, linear solvers and HPC aspects relevant to turbulent-flow simulations.

Related activities:
Exercise on stability of a simple time-integration scheme.
Short verification exercise based on grid refinement or manufactured solutions.
Discussion of computational cost and solver convergence in CFD simulations.

Full-or-part-time: 9h 30m
Theory classes: 3h 30m
Self study : 6h

Module 5: Turbulence modelling I: DNS, RANS and LES foundations

Description:
Introduction to the need for turbulence modelling in practical simulations.
DNS as a reference approach and its computational limitations.
Reynolds averaging, closure problem and basic RANS concepts.
Introduction to LES, spatial filtering, resolved and unresolved scales, subgrid-scale stresses and the relation between grid resolution and modelling.

Related activities:
Exercise comparing DNS, RANS and LES requirements for a given flow. Short assignment on the closure problem. Analysis of filtered fields or basic LES
quantities using simple data or illustrative examples.

Full-or-part-time: 13h 30m
Theory classes: 5h
Self study : 8h 30m

Module 6: Turbulence modelling II: advanced simulation and aerodynamic applications

Description:
Advanced topics in turbulence simulation and modelling. LES subgrid-scale models, wall modelling, hybrid RANS/LES approaches and model limitations.
Application to aerodynamic flows, including turbulent boundary layers, wakes, separated flows and flow-control problems.
Discussion of simulation setup, post- processing, interpretation of results and comparison between modelling strategies.

Related activities:
Hands-on session and practical work related to Assignment 2: Burgers'equation, spectral solution and LES modelling.
Computational or data-analysis
assignment involving turbulent-flow simulation results, comparison between modelling approaches and preparation of a short report and/or oral discussion.

Full-or-part-time: 13h
Theory classes: 4h 30m
Self study : 8h 30m

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GRADING SYSTEM

Any academic fraud, plagiarism or use or possession of unauthorised means in an assessment activity leads to a mark of zero (0) for the affected test or assignment. Furthermore, in accordance with the University's regulations, if disciplinary proceedings are initiated the subject is recorded as "Pending Assessment" until a decision is reached. These incidents are managed in accordance with the **Action Framework for Academic Integrity in Assessment at the UPC**.

Partial exam: 20%. Individual written test on the first part of the course.
Final exam: 35%. Individual written test covering the main theoretical and practical contents of the whole course.
Assignments: 45%. Two advanced computational assignments (22.5% each) involving report, numerical implementation, discussion of the results and, when appropriate, an individual oral defense.
Assignment 1: Algebra-based Navier-Stokes solver. Students start from a provided MATLAB code and implement and analyse a fractional-step method for the incompressible Navier-Stokes equations. The assignment focuses on spatial and temporal discretization, pressure-velocity coupling, solution of the pressure Poisson equation and simulation of a channel flow. Possible extensions include laminar validation cases, the relation between bulk and friction Reynolds numbers, mesh refinement, turbulent regimes, convective schemes, time-integration stability and computational cost. Students must submit a report and code, and the work may include an individual oral defense.

Assignment 2: Burgers' equation. Students solve Burgers' equation in Fourier space in order to study basic mechanisms of turbulence, including energy cascade, inter-scale interaction and the role of convective and diffusive terms. The assignment starts without a turbulence model and then includes a proposed LES model. Different Reynolds numbers and resolutions may be analysed, using any programming language. Students must submit a report and the corresponding code.

The assessment system includes mechanisms for the recovery of unsatisfactory results, in accordance with the academic regulations of the UPC and the ESEIAAT.

Recovery mechanism: Students who fail the course, or who fail the final exam, will have the option of taking a final recovery exam. This exam will be scheduled on the date established in the ESEIAAT academic calendar for the recovery of elective courses. The mark of this final recovery exam will be between 0 and 10 and will replace the final- exam mark only if it is higher. The assignments are not recoverable. After the recovery exam, the final mark will be recalculated as:

Final mark = 0,2*max(partial exam,recovery exam)+0.35*max (final exam,recovery exam) + 0.45*Assignments.

BIBLIOGRAPHY

Basic:
- Pope, S. B. Turbulent flows. Repr. with corr. Cambridge, UK: Cambridge University Press, 2003. ISBN 0521591252.
- Ferziger, Joel H.; Peric, Milovan; Street, Robert L. Computational methods for fluid dynamics [on line]. 4th ed. Cham, Switzerland: Springer, 2020 [Consultation: 20/07/2026]. Available on: https://link-springer-com.recursos.biblioteca.upc.edu/book/10.1007/978-3-319-99693-6. ISBN 9783319996936.
- Versteeg, H. K.; Malalasekera, W. An introduction to computational fluid dynamics: the finite volume method. 2nd ed. London: Pearson, 2007. ISBN 9780131274983.
- Sagaut, Pierre. Large eddy simulation for incompressible flows: an introduction [on line]. 3rd ed. Berlin: Springer, 2006 [Consultation: 20/07/2026]. Available on: https://link-springer-com.recursos.biblioteca.upc.edu/book/10.1007/b137536. ISBN 3540263446.

Complementary:
- Davidson, Peter Alan. Turbulence: an introduction for scientists and engineers. 2nd ed. Oxford: Oxford University Press, 2015. ISBN 9780198722595.
- Tennekes, H.; Lumley, J. L. A first course in turbulence. Cambridge: MIT Press, 1972. ISBN 0262200198.
- Wilcox, David C. Turbulence Modeling for CFD. 3rd ed. La Cañada: DCW Industries, 2006. ISBN 9781928729082.
- Moin, Parviz. Fundamentals of engineering numerical analysis. 2nd ed. Cambridge: Cambridge University Press, 2010. ISBN 9780521711234.