639 ADVANCED TURBULENCE
Spring 2024

INSTRUCTOR: Goodarz Ahmadi, Room 267 CAMP (315-268-2322)
gahmadi@clarkson.edu
Office Hours: Monday and Wednesday 12:30 - 3:30 pm

CLASS TIME Time: TT 9:30-10:45, Computer Lab, F 4:00-5:30, CAMP 163/172
(CAMP 177 for Lectures on ANSYS-FLUENT)

TEXT: None. Lecture notes are available on the web.

TA: Abbas Khanmohamdi, khanmoa@clarkson.edu
Office Hours: Friday 1:00-2:30 pm CAMP 275
Seyi Oluwadare, oluwadsr@clarkson.edu

Course Description

Review of viscous flow theory. Review of the instability of viscous flows. Origin of turbulence. Phenomenological theories of turbulence. Reynolds' equation. Energy budget and vorticity dynamics in turbulence. Free shear and internal flows. Turbulent boundary layer. Introduction to turbulence modeling. The k-ε and stress transport models. Recent developments in turbulence modeling, stress transport models, multipoint closure methods, and thermodynamical formulation. Turbulent diffusion, isotropic turbulence, and Karman-Howarth equation. Kraichnan's direct interaction approximation. Wiener-Hermite expansion approach. Characteristic functional formulation and Hopf's theory. Lundgren's probabilistic formulation and Chung's kinetic theory of turbulence. Direct and Large-Eddy simulation techniques. Proper orthogonal decomposition Techniques. Chaos and dynamical systems, stochastic Estimation.

Delivery Method

The course is offered in blended mode, both in-person in the class as well as online (synchronous). The lectures will be captured by Echo 360 and will be made available to students.

COURSE WEB SITE:

https://webspace.clarkson.edu/projects/fluidflow/public_html/courses/me639/index.html
https://sites.clarkson.edu/gahmadi/courses/me639/

Course Objectives

- To provide the students with a fundamental understanding of turbulent flows.
- To provide the students with an understanding of turbulence's stochastic and chaotic nature.
- To provide the students with the tools for modeling turbulent flows.
- To provide the students with an understanding of the statistical theories of turbulence.
- To provide the student with an understanding of simulation techniques in turbulent flows.
- To provide the student with an understanding of applications of turbulence in industry and environment.

Course Learning Outcomes

Objective 1: Students will demonstrate an understanding of the fundamental physics of turbulent flows.
Students will be able to analyze the transport of moment, energy, and vorticity in turbulent flows.

Objective 2: Students will be able to analyze simple shear, wall-bounded, and boundary layer flows using phenomenological models of turbulence. Students will demonstrate an understanding of advanced higher-order modeling of turbulent shear flows. Students will be able to analyze turbulent flows in complex regions using commercial codes.

Objective 3: Students will become familiar with the direct and large-eddy simulations of turbulent flows. Students will become familiar with the classical and modern statistical theories of turbulence.

Objective 4: Students will become familiar with the applications of turbulence in industry and the environment.

COURSE OUTLINE

Course Schedule & Graded Activities

Dates	Module Title	Learning Materials (readings, videos, etc.)	Activities
Week 1	**I. REVIEWS**	• Viscous Flow • Kinematics • Conservation Laws • Continuum Thermodynamics • Constitutive Equations	Homework
Week 2	**II. STABILITY**	• Linear Stability • Nonlinear and Energy Stability	Homework
Week 3-4	**III. CHAOS THEORY**	• Chaotic Response of Nonlinear Systems • Chaos and Turbulence	Homework
Week 5-6	**IV. PHYSICS OF TURBULENCE**	• Introduction to Physics of Turbulence • Reynolds Equation • Phenomenological Theories • Correlation and Spectrum, Length and Time Scales • Energy Equation • Vorticity Dynamics	Homework
Weeks 7	**V. TURBULENT SHEAR FLOWS**	• Free Shear Flows • Wall-bounded Shear Flows • Boundary Layer Flows	Computer Projects Exam-1
Weeks 8-12	**VI. TURBULENCE MODELING**	• Zero Equation Models - Eddy Viscosity - Mixing Length Hypothesis • One and Multi-equations Models - $k-\varepsilon$ Models - Stress Transport Models - Second-order Modeling - Thermodynamical Approach to Modeling	Homework
Weeks 13-14	**VII. NUMERICAL SIMULATION METHODS**	• Computational Modeling of Turbulent Flows - Commercial codes (ANSYS-FLUENT) • Direct Simulations	Homework

		• Large-Eddy Simulations - Subgrid-Scale Modeling	
Week 15-16	**VIII. STATISTICAL THEORIES OF TURBULENCE**	• Homogeneous Isotropic Turbulence - Karman-Howarth Equations • Probability Density Function Approach - Lundgren's Theory - Closure Methods - Chung's Kinetic Theory of Turbulence - Pope's Model • Proper Orthogonal Decomposition Method - Orthogonal Basis - First Order System - Navier-Stokes System - Low Dimensional Dynamical System - Applications to Modeling • Wiener-Hermite Expansion Method - Orthogonal Random Functions - Meecham's Theory • Kraichnan's Direct Interaction Theory - Infinitesimal Impulse Response - Eulerian Direct Interaction Approximation • Functional Approach - Hopf's Characteristic Functional Theory of Turbulence - Lewis-Kraichnan Approach • Stochastic Methods - Coherent Structures - Wavelet Transform - Stochastic Estimation - Pseudo-Flow Visualization	Homework Final Exam

COURSE TOPICS

I. REVIEWS

- Viscous Flow
- Instability
- Chaos and Turbulence

II. PHYSICS OF TURBULENCE

- Introduction to the Physics of Turbulence
- Reynolds Equation
- Phenomenological Theories
- Correlation and Spectrum, Length and Time Scales
- Energy Equation
- Vorticity Dynamics

III. TURBULENT SHEAR FLOWS

- Free Shear Flows
- Wall-bounded Shear Flows
- Boundary Layer Flows

IV. TURBULENCE MODELING

- Zero Equation Models
  - Eddy Viscosity
  - Mixing Length Hypothesis
- One and Multi-equations Models
  - $k-\varepsilon$ Models
  - Stress Transport Models
  - Second-order Modeling
  - Thermodynamical Approach to Modeling

NUMERICAL SIMULATION METHODS

- Computational Modeling of Turbulence
  - Commercial codes (ANSYS-FLUENT)
- Direct Simulations
- Large-Eddy Simulations
  - Subgrid-Scale Modeling

STATISTICAL THEORIES OF TURBULENCE

- Homogeneous Isotropic Turbulence
  - Karman-Howarth Equations
- Probability Density Function Approach
  - Lundgren's Theory
  - Closure Methods
  - Chung's Kinetic Theory of Turbulence
  - Pope's Model
- Proper Orthogonal Decomposition Method
  - Orthogonal Basis
  - First Order System
  - Navier-Stokes System
  - Low Dimensional Dynamical System
  - Applications to Modeling
- Wiener-Hermite Expansion Method
  - Orthogonal Random Functions
  - Meecham's Theory
- Kraichnan's Direct Interaction Theory
  - Infinitesimal Impulse Response
  - Eulerian Direct Interaction Approximation
- Functional Approach
  - Hopf's Characteristic Functional Theory of Turbulence
  - Lewis-Kraichnan Approach
- Stochastic Methods
  - Coherent Structures
  - Wavelet Transform
  - Stochastic Estimation
  - Pseudo-Flow Visualization

EVALUATION METHOD:

Exam 1 (March 15, 4:00-5:15, CAMP 178) 25%
Exam 2 (Final Exam Week) 35%
Projects 30% (Project 1, 10%; Project 2, 20%)
Homework 10%

Grading

Grade Ranges

Graduate Letter Grades

Course Average	Grade	Quality Points
97+	A+	4.0
93-96	A	4.0
90-92	A-	3.667
87-89	B+	3.334
84-86	B	3.0
80-83	B-	2.667
76-79	C+	2.334
70-75	C	2.0
<70	F	0

Course Policies

Etiquette Expectations & Learner Interaction

Educational institutions promote the advancement of knowledge through positive and constructive debate--both inside and outside the classroom. Please visit and follow: Netiquette and Electronic Learner Interaction Guidelines.

Institutional Policies

Institutional Policies & Regulations

Academic Integrity

Students are expected to abide by the standards of academic honesty, as described in the Clarkson Regulations. The work or words of others must be properly cited. Please refer to Clarkson Library's Guide to Plagiarism and Citing Sources.

Students with Disabilities Policy

Clarkson University welcomes inquiries and applications from individuals who have disabilities. Information relating to disabling conditions is not a determining factor in admission decisions. The University strives to make all facilities and programs accessible to students with disabilities by providing appropriate academic adjustments and other appropriate modifications (accommodations) as necessary. Timely notification of any need for accommodations due to a disability is encouraged so that the Office of Accommodative Services (OAS) may provide for students in an efficient manner.

For more information or other appropriate campus referrals, contact:

Director of Accommodative Services
Clarkson University
PO Box 5645
Potsdam, NY 13699-5635
Phone: 315-268-7643
Fax: 315-268-2400
Email: oas@clarkson.edu
Office of Accessibility Services Website

Instructor Participation

During this course, as your instructor, you can expect me to

- Respond to emails and voicemails within 1 day
- Grade activities and assessments within 3 days
- Be an active participant on the discussion board

REFERENCES

1. J. Y. Tu, K. Inthavong, and G. Ahmadi, "Computational Fluid and Particle Dynamics in the Human Respiratory System," Springer, New York (2013). https://www.springer.com/gp/book/9789400744875
2. J.O. Hinze, "Turbulence," McGraw Hill (1975). https://www.amazon.com/Turbulence-McGraw-Hill-mechanical-engineering-Hinze/dp/0070290377
3. H. Tennekes and J.L. Lumley, "A First Course in Turbulence," MIT Press (1981). https://mitpress.mit.edu/books/first-course-turbulence
4. S. Pope, "Turbulent Flows," Cambridge University Press, (2000).
5. J.L. Lumley, "Stochastic Tools in Turbulence, "Academic Press (1970).
6. B.E. Launder and Spalding, "Mathematical Models of Turbulence," Academic Press (1972).
7. P. Bradshaw, T. Cebeci and J.H. Whitelaw, "Engineering Calculation Methods for Turbulent Flows," Academic Press (1981).
8. P. Bradshaw, "Turbulence," Springer-Verlag (1976).
9. A.S. Monin and A.M. Yaglom, "Statistical Fluid Mechanics: Mechanics of Turbulence, Vol. 1 and Vol. 2," MIT Press (1975).
10. D.C. Leslie, "Developments in the Theory of Turbulence," Clarendon Press (1973).
11. M.M. Stanisic, "The Mathematical Theory of Turbulence," Springer-Verlag (1985).
12. M. Lesieur, "Turbulence in Fluids," Kluwer Academic Publishers (1990).