Boundary Layers and Convection
ASEN-5121-001(B)
Spring Semester 2023

Syllabus

(**Revised by:** J. Farnsworth - January 16, 2023)

Time: Tue. & Thurs. 2:30pm-3:45pm

Classroom: AERO 232

Instructor: John Farnsworth (Assistant Professor)
Office: AERO 365
Phone:
Email: john.farnsworth@colorado.edu

Office Hours: Tuesday 4:00 - 5:00 PM MT (AERO 365 / Zoom)
Thursday 4:00 - 5:00 PM MT (AERO 365 / Zoom)

Teaching Assistant: DeAnna Sewell Gilchrist
Email: deanna.sewell@colorado.edu
Office Hours: Monday 3:00 - 4:00 PM MT (AERO 302 / Zoom)
Wednesday 5:30 - 6:30 PM MT (AERO 302 / Zoom)

Virtual Office/Meeting Room:
Passcode: prandtl

Website: Canvas (https://canvas.colorado.edu)

Slack Workspace: To help better facilitate online communication the following Slack Workspace has been set-up for this course: Boundary Layers (ASEN 5121). Please note that you are not required to use this and all course wide notifications will still be sent out also via notifications through the course webpage, but we believe this application will help improve communication and collaboration within the course. To join the workspace please use the following link:

Objective: To establish a fundamental understanding of the theory associated with viscous flow and to introduce methods for performing engineering calculations of skin friction and heat transfer rates.

Description: This course presents an introduction to the principles of viscous fluid flow and methods for performing engineering calculations of quantities such as skin friction and heat transfer rates in boundary layers. The first portion of the course material will focus on basic principles of fluid mechanics. We will derive the Navier-Stokes equations and discuss some simple solutions to these equations. The second portion of the course will concentrate on the application of these principles to boundary layers. We will derive the boundary layer equations and discuss their approximate and almost exact solutions.

Prerequisites: B+ or better in ASEN 3111: Aerodynamics (Undergraduate Level) or equivalent course. Recommended completion of ASEN 5051: Fundamental Fluid Dynamics (Graduate Level), but not required.

Required Text:

F. White and J. Majdalani, *Viscous Fluid Flow.* McGraw-Hill, 4th ed., 2022. Webpage
Note: *The class will be using the latest edition of this book, but students are welcome to use any edition of the textbook to follow along with the reading (i.e. an earlier edition or an international edition). There is no electronic/online access to this book from the CU Library, but a physical copy of this book has also been placed on the course reserves at the Gemmill (Engineering, Math, Physics) Library.*

Supplemental References:

1. J. Schetz and R. Bowersox, *Boundary Layer Analysis.* AIAA Education Series, 2nd ed., 2011. Webpage / Online Supplemental Material / CU Library Online Access
Note: *Electronic Access to this textbook is available through the CU Library Website using the above link or by searching for this title on the CU Library Webpage. Additionally, PDF copies of the individual chapters can be downloaded from the above site. To access you may have to be on the campus network, logged into the campus VPN from off-campus, or may be asked to log in with your campus credentials to access the text.*

2. H. Schlichting and K. Gersten, *Boundary Layer Theory.* Springer, 9th ed., 2017. Webpage
Note: *An electronic (PDF) copy of this book can be downloaded through the publisher webpage (above) while you are connected to the CU Campus Network as a part of the CU Library subscriptions.*

3. P. Kundu, I. Cohen and D. Dowling, *Fluid Mechanics.* Academic Press, 6th Edition, 2015. Webpage / CU Library Online Access
Note: *The CU library provides full online access to multiple editions of this text. The link posted above should take you to the library search page from which you can access the texts. To access you may have to be on the campus network, logged into the campus VPN from off-campus, or may be asked to log in with your campus credentials to access the text.*

4. M. Van Dyke, *An Album of Fluid Motion.* Parabolic Press, 1982.
Note: *Online access to this book is provided by http://www.efluids.com/ and specifically a copy of this book can be downloaded on a public Google drive through this link: Album of Fluid Motion PDF.*

5. *National Committee for Fluid Mechanics Films (NCFMF)*, Shapiro.
Note: *Online archive at: http://web.mit.edu/hml/ncfmf.html.*

Content: An outline of the course content is included below:

1. Introduction to viscous flows.
2. Concept of a fluid; Kinematics of fluid motion; Properties of a fluid.
3. Conservation laws for a continuum: mass, momentum and energy; Navier-Stokes equations.
4. Simple viscous solutions of Navier-Stokes equations, for example: Couette flow, Poiseuille flow, and plane stagnation flow.
5. Incompressible, laminar boundary layers: boundary layer equations, flow over a flat plate (Blasius solution), wedge flows (Falkner-Skan solution), free-shear flows, integral methods and approximate solution techniques, three-dimensional boundary layers, separation, stability, transition to turbulence.
6. Thermal boundary layers: uncoupled solution to energy equation.
7. Compressible, laminar boundary layers: boundary layer equations, approximate and exact solutions, special topics including real gas effects and shock.
8. Turbulent boundary layers: nature of turbulent flow, RANS equations, turbulent boundary layer equations, turbulent pipe & channel flow, turbulent flow over a flat plate, summary of turbulence modeling formulations

Student Learning Outcomes: The basic learning objectives for the course are outlined below:

1. Understand concept of viscous fluid flows and basic conservation laws (to derive basic governing equations).
2. Be able to find solution to simple viscous flows.
3. Ability to derive boundary layer equations and find their solution (including similarity analysis and integral methods).
4. Develop basic understanding of transition and turbulence as well as compressible boundary layers.
5. Understand the structure, nature, and modeling of turbulent boundary layers

Class Format: The class meets twice a week for one hour and fifteen minutes of formal lecture and discussion. All lectures will be be recorded and posted on the course website for asynchronous viewing after the scheduled lecture period, and all students actively enrolled in the course will have access to the lecture videos. If students are unable to participate in-person or are registered for the distance section then they are encouraged to participate virtually in an asynchronous format by watching the lecture videos and posting questions/discussion on the course Slack Workspace. Office hours will be held in a hybrid format (simultaneously in-person and over zoom) using the Zoom web-link provided above. The format may be adapted through the semester depending upon attendance and demand. All technical questions on course content should be asked during lecture, office hours, or on the course Slack Workspace. One-on-one meetings with the instructor will only be scheduled to address individual administrative or academic issues.

Course Website and Course Communications: There will be a class website on Canvas. All relevant documents and course materials will be posted to this site throughout the semester. Please check it regularly to see what has been posted. All course announcements outside of lecture will be sent as Canvas Announcements, so it is the student's responsibility to make sure their Canvas settings are appropriately configured to receive these announcements.

Students should only e-mail the teaching team if they have a pressing logistical or health issue (these include personal administrative and academic questions that the student does not feel comfortable asking in front of the class). The teaching team will aim to respond to e-mails within one business day. All general questions on assignments, quizzes, exams, and course content should be asked during lecture, office hours, or on the course Slack Workspace in a public forum to ensure that other students with similar questions receive a consistent response and to limit unnecessary redundancy in communication.

Grading: The table below presents the grading structure for the course.

Concept Quizzes	10%
Homework Assignments	15%
Midterm Concept Exams	25%
Final Project	20%
Final Concept Exam	30%
Total	**100%**

Grades will be posted to the class website (Canvas). This class is not graded on a "curve"; there are absolute expectations of performance. However, the Professor reserves the right to normalize the class grades based on the highest performance in the class.

Concept Quizzes: Weekly concept quizzes will be conducted through the class webpage on Canvas. Concept quizzes will focus on the conceptual content primarily associated with the lecture and readings during the week they are scheduled, but can also include other content covered in prior weeks. The concept quizzes will be released on Monday at 12:00 am and will be due the following Sunday at 11:59 pm. Students will have fifteen minutes to complete each quiz, and students will be able to take each concept quiz as many times as they like before it is due. This allows students to retake each quiz to help them identify, practice, and comprehend important concepts until they have mastered the content. The concept quizzes will be closed-book and collaboration is prohibited. There will be no make-up concept quizzes, however the lowest two quiz grades will be dropped.

Homework Assignments: Homework problem sets will be assigned approximately every two weeks during the first two-thirds of the semester. Homework assignments will always be due by 11:59pm on Thursday. Students will submit their completed homework electronically using Gradescope, which they can access through the class website on Canvas. Late homework assignments can be submitted, but their value will be aged 20% per day (24 hrs) after the deadline up until the release of the solution at which point a student will receive a 0% for the homework. The lowest homework grade will be dropped from the homework assignment average.

Homework assignments will focus on problem solving to develop and assess a student's ability to implement the prediction and analysis tools discussed in class. Students can expect the homework assignments to have challenging and involved problems that may take over a week of effort (off and on) to complete with the discussion and assistance from the instructor. Some assignments require access to a computer, basic programming skills, and familiarity with some programming languages and/or environments similar to what is covered in introductory computing courses.

Collaboration is permitted on homework. You may discuss the means and methods for formulating and solving problems and even compare answers, but you are not free to copy someone's assignment. **Copying material from any resource (including solutions manuals) and submitting it as one's own is considered plagiarism and is an Honor Code violation (and will be reported as such).** Remember, the less you think about the problems yourself, the less you actually learn.

Homework assignments are not meant to be an assessment of the students ability, but rather a formative learning tool to practice the methods discussed in lecture. As a result, the Homework assignments will be graded based upon effort and completion. Students should attempt to solve every problem as completely as possible. If a student turns in a blank page or minimally restates the problem with no clear attempt at solution they will receive zero credit for the problem. Students will receive full credit for working through a problem to a clear conclusion or answer (no matter the correctness of the result). Partial credit will be given, based upon the discretion of the Instructor and TA, depending upon the degree-to-completion of each homework problem.

Solutions will be released for each homework set and students should review them and compare them with their submissions to understand where they may have made a mistake.

Final Project: During the last one third of semester a comprehensive boundary layer prediction and analysis project will be assigned in place of regular homework assignments. Students will be expected to demonstrate the prediction of the expected boundary layer behavior (laminar and turbulent), based upon the theories and models discussed in the class throughout the semester. These predictions will be compared with actual boundary layer data from experiments and simulations, provided by the instructor and analyzed by the students, to demonstrate a comprehensive understanding of the subject. The project will due by 11:59pm on Thursday 04 May 2023 (the last day of class). To summarize the project activities and results students will each submit a report, no longer than 10 pages inclusive of all figures, tables, and references in a PDF format to Canvas.

As with the homework assignments, collaboration is permitted ,but students are each expected to complete an individual project, in full. You may discuss the means and methods for formulating and solving problems and even compare answers, but you are not free to copy someone's assignment. **Copying material from any resource (including textbooks, technical papers and reports) and submitting it as one's own is considered plagiarism and**

is an Honor Code violation (and will be reported as such). Additionally, each report will be analyzed for plagiarism to ensure that it is the original work of the student. Additional details on the expectations and implementation will be provided when the project is officially assigned and released to the students around week 10 (the week before spring break).

Concept Exams: Two concept exams, one midterm and one final, will be utilized to asses the students aptitude in the course material. The exams will be closed-book and collaboration will not be permitted. The exams will focus on conceptual assessment of understanding of the content discussed in the class. Much of the content covered in these exams will build-off of the questions in the concept quizzes, however in addition to true/false, multiple choice, and fill in the blank questions students should also expect short answer questions that require them to explain, drawn, and annotate important theories and concepts covered throughout the course. Exams will be timed appropriately for the material covered (1 hr. for the midterm exam and 2 hrs for the final) and students must either attend the exam period in-person in the assigned classroom on the defined exam days or identify an exam proctor and time to take the exam (if they are participating in the class in an asynchronous remote mode).

Collaboration on exams, using another student's work as your own, or allowing another student to use your work as their own is academic misconduct and is not tolerated. If you are caught in any of these activities, you will receive a grade of "F" for the course and a report as an Honor Code Violation for further review and action. The Final Concept Exam will administered during the assigned final exam period for the course and will be cumulative for the semester. Additionally students should be aware of the university's Final Exam Policy.

Exam Schedule:

Midterm "Concept" Exam:
Date: Thursday 23 March 2023
Time: 2:30pm - 3:45pm
Location: AERO 232

Final "Concept" Exam (Cumulative):
Date: Sunday 07 May 2023
Time: 4:30pm - 7:00pm
Location: AERO 232 (tentative)

Classroom Behavior: Both students and faculty are responsible for maintaining an appropriate learning environment in all instructional settings, whether in person, remote or online. Those who fail to adhere to such behavioral standards may be subject to discipline. Professional courtesy and sensitivity are especially important with respect to individuals and topics dealing with race, color, national origin, sex, pregnancy, age, disability, creed, religion, sexual orientation, gender identity, gender expression, veteran status, political affiliation or political philosophy. For more information, see the classroom behavior policy, the Student Code of Conduct, and the Office of Institutional Equity and Compliance.

Requirements for COVID-19: As a matter of public health and safety, all members of the CU Boulder community and all visitors to campus must follow university, department and building requirements and all public health orders in place to reduce the risk of spreading infectious disease. CU Boulder currently requires COVID-19 vaccination and boosters for all faculty, staff and students. Students, faculty and staff must upload proof of vaccination and boosters or file for an exemption based on medical, ethical or moral grounds through the MyCUHealth portal.

The CU Boulder campus is currently mask-optional. However, if public health conditions change and masks are again required in classrooms, students who fail to adhere to masking requirements will be asked to leave class, and students who do not leave class when asked or who refuse to comply with these requirements will be referred to Student Conduct and Conflict Resolution. For more information, see the policy on classroom behavior and the Student Code of Conduct. If you require accommodation because a disability prevents you from fulfilling these safety measures, please follow the steps in the "Accommodation for Disabilities" statement on this syllabus.

If you feel ill and think you might have COVID-19, if you have tested positive for COVID-19, or if you are unvaccinated or partially vaccinated and have been in close contact with someone who has COVID-19, you should stay home and follow the further guidance of the Public Health Office (contacttracing@colorado.edu). If you are fully vaccinated and have been in close contact with someone who has COVID-19, you do not need to stay home; rather, you should self-monitor for symptoms and follow the further guidance of the Public Health Office (contacttracing@colorado.edu).

In this class, if you are sick or quarantined, please notify the instructor of your absence from in-person activities and continue in a completely remote mode until you are able and allowed to return to campus. Please note that for health privacy reasons you are not required to disclose to the instructor the nature of your illness, however you are welcome to share information you feel necessary to protect the health and safety of others in the course.

Accommodation for Disabilities: If you qualify for accommodations because of a disability, please submit your accommodation letter from Disability Services to your faculty member in a timely manner so that your needs can be addressed. Disability Services determines accommodations based on documented disabilities in the academic environment. Information on requesting accommodations is located on the Disability Services website. Contact Disability Services at 303-492-8671 or dsinfo@colorado.edu for further assistance. If you have a temporary medical condition, see Temporary Medical Conditions on the Disability Services website.

Preferred Student Names and Pronouns: CU Boulder recognizes that students' legal information doesn't always align with how they identify. Students may update their preferred names and pronouns via the student portal; those preferred names and pronouns are listed on instructors' class rosters. In the absence of such updates, the name that appears on the class roster is the student's legal name.

Honor Code: All students enrolled in a University of Colorado Boulder course are responsible for knowing and adhering to the Honor Code. Violations of the Honor Code may include, but are not limited to: plagiarism, cheating, fabrication, lying, bribery, threat, unauthorized access to academic materials, clicker fraud, submitting the same or similar work in more than one course without permission from all course instructors involved, and aiding academic dishonesty. All incidents of academic misconduct will be reported to Student Conduct & Conflict Resolution (honor@colorado.edu; 303-492-5550). Students found responsible for violating the Honor Code will be assigned resolution outcomes from the Student Conduct & Conflict Resolution as well as be subject to academic sanctions from the faculty member. Additional information regarding the Honor Code academic integrity policy can be found on the Honor Code website.

Sexual Misconduct, Discrimination, Harassment and/or Related Retaliation: CU Boulder is committed to fostering an inclusive and welcoming learning, working, and living environment. University policy prohibits sexual misconduct (harassment, exploitation, and assault), intimate partner violence (dating or domestic violence), stalking, protected-class discrimination and harassment, and related retaliation by or against members of our community on- and off-campus. These behaviors harm individuals and our community. The Office of Institutional Equity and Compliance (OIEC) addresses these concerns, and individuals who believe they have been subjected to misconduct can contact OIEC at 303-492-2127 or email cureport@colorado.edu. Information about university policies, reporting options, and support resources can be found on the OIEC website.

Please know that faculty and graduate instructors have a responsibility to inform OIEC when they are made aware of any issues related to these policies regardless of when or where they occurred to ensure that individuals impacted receive information about their rights, support resources, and resolution options. To learn more about reporting and support options for a variety of concerns, visit Don't Ignore It.

Religious Holidays: Campus policy regarding religious observances requires that faculty make every effort to deal reasonably and fairly with all students who, because of religious obligations, have conflicts with scheduled exams, assignments or required attendance. In this class, you must let the instructor know of any such conflicts within the first two weeks of the semester so that they can work with you to make reasonable arrangements.

See the campus policy regarding religious observances for full details.

Schedule

Week	***Dates***	***Tuesday***	***Thursday***	***Readings***
1	Jan. 17 & 19	Syllabus & Preliminary Concepts	Properties of a Fluid	**RR:** 1-1 – 1-3
2	Jan. 24 & 26	Cons. of Mass Cons. of Momentum	Cons. of Energy Boundary Conditions	**RR:** 1-4, 2-1 – 2-6
3	Jan. 31 & Feb. 2	Mathematical Character & Nondimensional Forms	Vorticity Streamfunction	**RR:** 2-8 – 2-11 **SR:** 2-7, 2-12
4	Feb. 7 & 9	Control Volume Formulations	Couette & Poiseuille Flow	**RR:** 2-13, 3-1 – 3-3 **SR:** 2-12, 3-4, 3-5
5	Feb. 14 & 16	Similarity Solutions	Plane Stagnation Flow	**RR:** 3-8 **SR:** 3-6 – 3-9
6	Feb. 21 & 23	Laminar Boundary Layer Equations	BL Sim. Solutions (Blasius Soln.)	**RR:** 4-1 – 4-3.1-2
7	Feb. 28 & Mar. 2	BL Sim. Solutions (Falkner-Skan Soln.)	Free Shear Flows (Planar Jets & Wakes)	**RR:** 4-3.3 – 4-4 **SR:** 4-5
8	Mar. 7 & 9	Approximate Integral Methods	Three-Dimensional Laminar BLs	**RR:** 4-6, 4-11 **SR:** 4-7 – 4-10, 4-12, 4-13
9	Mar. 14 & 16	Compressible Boundary Layer Equations	Compressible, Laminar Boundary Layer Solutions	**RR:** 7.1 – 7.3
10	Mar. 21 & 23	Special Topics: Real Gas Effects & Shock Wave BL Interactions.	**Midterm "Concept" Exam**	**RR:** Schetz 5.12-5.14
11	Mar. 28 & 30	**No Class** (Spring Break)	**No Class** (Spring Break)	
12	Apr. 4 & 6	Stability of Inviscid Laminar Flows (K-H Instability)	Stability of Parallel Viscous Flows (O-S Eqn.)	**RR:** 5-1 – 5-2 **SR:** Kundu C11
13	Apr. 11 & 13	Parametric Effects in the Linear Stability Theory	Prediction, Classification, & Evolution of Transition	**RR:** 5-3 – 5-5
14	Apr. 18 & 20	Nature of Turbulent Flow & RANS Equations	Turbulent BL Equations & Velocity Profiles	**RR:** 6-1 – 6-4
15	Apr. 25 & 27	Turbulent Pipe & Channel Flow	Turbulent BL on a Flat Plate	**RR:** 6-5 – 6-6
16	May 2 & 4	Summary of Turbulence Modeling Formulations	Catch-Up & Review	**RR:** 6-7

- **Final "Concept" Exam: 4:30 pm MT - 7:00 pm MT Sunday 07 May 2023**
- Readings are from the text book: White & Majdalani, *Viscous Fluid Flow*, 4th Ed.
- **RR** = *"Required Reading"* where as **SR** = *"Suggested Reading"*.
- Prepared By (Date): John A. N. Farnsworth (January 16, 2023)