# Boundary Layers and Convection
# ASEN-5121-001(B)
Spring Semester 2022

## Syllabus

(**Revised by:** J. Farnsworth - January 14, 2022)

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

**Physical Classroom:** AERO N240

**Instructor:** Asst. Prof. John Farnsworth
Office: AERO 365
Phone: (303)735-7287
Email: john.farnsworth@colorado.edu
Office Hours: TBD

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

**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:** Graduate Fluids (ASEN 5051), B+ or better in Aerodynamics (ASEN 3111) or permission of instructor.

**Required Text:**
J. Schetz and R. Bowersox, *Boundary Layer Analysis*. AIAA Education Series, 2nd ed., 2011.
**Webpage:** `https://arc.aiaa.org/doi/book/10.2514/4.868245`
**Online Supplemental Material:** `https://arc.aiaa.org/doi/suppl/10.2514/4.868245/suppl_file/index.html`
**eBook Access - CU Library:** `https://ebookcentral.proquest.com/lib/ucb/detail.action?docID=3111690`
**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. A physical copy of this book has also been placed on the course reserves at the Gemmill (Engineering, Math, Physics) Library.*

**Supplemental References:**

1. F. White, *Viscous Fluid Flow*. McGraw-Hill, 3rd ed., 2006.
**Webpage:** https://www.mheducation.com/highered/product/viscous-fluid-flow-white/M0072402318.html **Note:** *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.*

2. H. Schlichting and K. Gersten, *Boundary Layer Theory*. Springer, 9th ed., 2017.
**Webpage:** https://www.springer.com/us/book/9783662529171
**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. A physical copy of this book has also been placed on the course reserves at the Gemmill (Engineering, Math, Physics) Library.*

3. *An Album of Fluid Motion*, Van Dyke, Parabolic Press, 1982.
**Note:** *Online access to this book is provided by https://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.*

4. *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
   - Properties of a Fluid / Laminar Transport Properties
   - Boundary Conditions
   - Conservation of Mass
   - Conservation of Momomentum (Navier-Stokes Equations)
   - Conservation of Energy
   - Non-dimensional Form of Conservation Equations
   - Boundary Layer Assumptions & Equations
   - Separation & Kutta Condition
   - Non-Newtonian Fluid Flow
   - Laminar vs. Turbulent Flow
2. Integral Boundary Layer Equations & Analysis
   - Definition of a Control Volume
   - Integral Momentum Equation
   - Boundary Layer Thickness Definitions

- Pohlhausen Method
- Thwaites-Walz Method
- Impact of Suction & Injection
- Integral Energy Equation
- Unheated Starting Length Problem
- Varying Wall Temperature & Pressure Gradients
- Integral Species Equation
- Relationship between Wall Friction, Heat Transfer, & Mass Transfer

3. Incompressible Laminar Boundary Layer Flows
   - Exact Solutions for Parallel Flows (Couette, Poiseuille, Stokes Flows)
   - Similarity Solutions for the Momentum Equation
   - Blasius Solution for a Flat Plate
   - Falkner-Skan Solutions for a Flat Plate with Pressure Gradient
   - Similarity Solutions for the Energy Equation
   - Similarity Solutions with Suction & Injection
   - Summary of Numerical Solution Methods
4. Compressible Laminar Boundary Layer Flows
   - Viscous Heating
   - Influence of Prandtl Number
   - Compressiblity Transforms
   - Integral Method for Compressible Flow
   - Solution for Compressible Flow over a Flat Plate
   - Stagnation Point Solutions for Compressible Flow
   - Flows with Mass Transfer
   - Real Gas Effects
   - Pressure Gradients & Separation in High-Speed Flows
   - Interactions in Hypersonic Flows
5. Laminar Free Shear Flows
   - Simple Shear Layers
   - Jets & Wakes
6. Transition to Turbulent Flows
   - Stability of Laminar Flows (In General)
   - Stability of an Inviscid Flows (Kelvin-Helmholtz Instability)
   - Stability of Parallel Flows
   - Prediction of Transition
   - Classification & Evolution of Transition

  - Impact of Freestream Turbulence, Pressure Gradient, Wall Roughness, Mach Number, Suction/Injection, and Heating/Cooling on Transition

7. Incompressible Turbulent Boundary Layer Flows
   - The Nature of Turbulent Flow
   - Reynolds-Averaged Navier-Stokes Equations
   - Description of the Mean Flow over a Flat Plate
   - Effect of Roughness, Suction/Injection, & Pressure Gradient
   - Other Empirical Turbulence Information
   - Mean Flow Integral Methods
   - Mean Flow Model for Eddy Viscosity and Mixing Length
   - Summary of other Turbulence Modeling Approaches

**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.

**Class Format:** The class meets twice a week for an hour and fifteen minutes of formal lecture and discussion. Prior to each lecture, students should complete the assigned readings to make the most efficient usage of time and to address any questions they may have on the content. The lectures will be administered in a hybrid format, allowing for both in-person and online synchronous attendance. The lectures will also be recorded using the video and audio capture capabilities within the classroom to allow for asynchronous viewing. The lecture recordings will be made available through the course website within 24 hrs. following each lecture.

In addition to lecture, office hours will be held twice per week for one hour each. Office hours will also be administered in an hybrid fashion allowing for in-person and online synchronous attendance. Discussion during office hours will not be recorded. Office hours will be used to address student questions about the course content, homework assignments, and projects. Generally, office hours will be used to address public questions open to the full class. If a student has concerns that they would like to discuss with the professor in private, they are encouraged to schedule an individual meeting outside of office hours.

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

| | |
|---|---|
| Concept Quizzes | 10% |
| Homework Assignments | 25% |
| Mid-term Concept Exams | 20% |
| Final Project | 25% |
| Final Concept Exam | 20% |
| **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 quiz grade 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.

**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. The project will include two parts: 1) the analysis of experimental boundary layer data (provided by the instructor) and 2) the computational simulation of boundary layers using computational fluid dynamics. As part of this project, students will be expected to demonstrate the prediction and analysis methods and tools developed through the semester on actual boundary layer data to demonstrate a comprehensive understanding of the subject. The project will due by 11:59pm on April 28, 2022 (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:** Three concept exams, two mid-term 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 (30-45 min for the midterm exams and 1.5 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 mode). Note that the remainder of the lecture period will be used to present new materiel after the mid-term concept exams, on the days which they are assigned.

**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:**

**Mid-term Concept Exam 1:**
Date: Thursday 10 February 2022
Time: 2:30pm - 3:45pm
Location: AERO N240

**Mid-term Concept Exam 2:**
Date: Thursday 17 March 2022
Time: 2:30pm - 3:45pm
Location: AERO N240

**Final Concept Exam (Cumulative):**
Date: Sunday 01 May 2022
Time: 4:30pm - 7:00pm
Location: AERO N240 (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 policies on classroom behavior and the Student Conduct & Conflict Resolution policies.

**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. Students who fail to adhere to these 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.

CU Boulder currently requires masks in classrooms and laboratories regardless of vaccination status. This requirement is a precaution to supplement CU Boulder's COVID-19 vaccine requirement. Exemptions include individuals who cannot medically tolerate a face covering, as well as those who are hearing-impaired or otherwise disabled or who are communicating with someone who is hearing-impaired or otherwise disabled and where the ability to see the mouth is essential to communication. If you qualify for a mask-related accommodation, please follow the steps in the "Accommodation for Disabilities" statement on this syllabus. In addition, vaccinated instructional faculty who are engaged in an indoor instructional activity and are separated by at least 6 feet from the nearest person are exempt from wearing masks if they so choose.

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).

**Class Specific Policies:** Generally speaking, late submissions of assignments will not be accepted, and there will be no make-up quizzes or exams. That being said please contact the instructor if you are unable to submit an assignment or take a quiz or exam due to illness, technical issues, or other challenging extenuating circumstances. Reasonable accommodations will be made, where appropriate, provided you contact the instructor before the assignment due date or quiz/exam date. Specifically, students should contact the professor via a direct email at least 24hrs ahead of the specific deadline or quiz/exam. During standard class periods, when exams are not being administered, students are not required to notify the professor of absences due to illness and quarantine. If a student tests positive for COVID-19, they are NOT required to disclose this to the professor. Note that based upon current health situation of the professor and/or students, the professor may move class or office hours to a remote format in order to protect the health and safety of the full class. For these situations, the professor will aim to provide the class notification at least 24hrs ahead of time via an announcement through the course website.

**Accommodations 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 academic integrity policy. 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 the Honor Code (honor@colorado.edu; 303-492-5550). Students found responsible for violating the academic integrity policy will be subject to nonacademic sanctions from the Honor Code as well as 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. The university will not tolerate acts of sexual misconduct (harassment, exploitation, and assault), intimate partner violence (dating or domestic violence), stalking, or protected-class discrimination or harassment by or against members of our community. Individuals who believe they have been subject to misconduct or retaliatory actions for reporting a concern should contact the Office of Institutional Equity and Compliance (OIEC) at 303-492-2127 or email cureport@colorado.edu. Information about university policies, reporting options, and the 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 incidents of sexual misconduct, dating and domestic violence, stalking, discrimination, harassment and/or related retaliation, to ensure that individuals impacted receive information about their rights, support resources, and reporting 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, please notify the professor as soon as possible and at least one week prior to any assignment deadline or exam/quiz which conflicts with religious obligations; so that appropriate accommodations can be made.

See the campus policy regarding religious observances for full details.

## Schedule (Tentative)

| *Week* | *Dates* | *Tuesday* | *Thursday* | *Assignments* |
|---|---|---|---|---|
| 1 | Jan. 11 & 13 | Syllabus & Introductory Thoughts | Properties of a Fluid Boundary Conditions | **R:** 1.1 - 1.3 |
| 2 | Jan. 18 & 20 | Cons. of Mass Cons. of Momentum | Cons. of Energy Non-dimensional Form | **R:** 1.5, 3.1 - 3.7 |
| 3 | Jan. 25 & 27 | Boundary Layer Assumptions & Equations | Summary of Separation, Non-Newtonian Fluids & Laminar/Turbulent Flow | **R:** 1.4, 1.6-1.9 |
| 4 | Feb. 1 & 3 | Integral Momentum Eqn. & BL Thickness Definitions | Pohlhausen Method & Thwaites-Walz Method | **R:** 2.1 - 2.3 |
| 5 | Feb. 8 & 10 | Integral Energy Eqn. & Solutions | **Concept Exam 1** Integral Species Eqn. | **R:** 2.4 - 2.8 |
| 6 | Feb. 15 & 17 | Couette, Poiseuille, & Stokes Flows | Similarity Solutions (Blasius & Falkner-Skan) | **R:** 4.1 - 4.3 |
| 7 | Feb. 22 & 24 | Similarity Solutions for Energy Eqn. & Mass Inj. | Summary of Numerical Solution Methods | **R:** 4.4-4.5, 4.7 |
| 8 | Mar. 1 & 3 | Viscous Heating & Inf. of Prandtl Number | Comp. Transformations Comp. Flow Int. Method | **R:** 5.1-5.7 |
| 9 | Mar. 8 & 10 | Exact Solutions (Flat Plate & Stag. Point) | Real Gas Effects, Press. Grad. Effects, & Separation | **R:** 5.8 - 5.14 |
| 10 | Mar. 15 & 17 | Free Shear Flows (Layers, Jets, & Wakes) | **Concept Exam 2** Instability in Laminar Flows | **R:** 9.1-9.2, |
| 11 | Mar. 22 & 24 | **No Class** (Spring Break) | **No Class** (Spring Break) | |
| 12 | Mar. 29 & 31 | Stability of Inviscid & Parallel Flows | Prediction, Classification, & Evolution of Transition | **R:** 6.1 - 6.5 |
| 13 | Apr. 5 & 7 | Summary of Impacts on Transition | Nature of Turbulent Flow & RANS Equations | **R:** 6.6, 7.1 - 7.2, 7.5 |
| 14 | Apr. 12 & 14 | Turbulent Mean Flow over a Flat Plate | Summary of Effects and Other Empirical Information for Turbulent BL | **R:** 7.3 - 7.4 |
| 15 | Apr. 19 & 21 | Mean Flow Turbulent Transport Formulations & Integral Methods | Eddy Viscosity & Mixing Length Models | **R:** 7.6 - 7.8 |
| 16 | Apr. 26 & 28 | Summary of other Turbulence Model Formulations | Catch-Up & Review | **R:** 7.9 - 7.15 |