# AE 480 – Hypersonic Aerothermodynamics

**Fall 2023**

## Instructor Information

| Instructor | Email | Office Location & Hours |
| --- | --- | --- |
| Francesco Panerai | fpanerai@illinois.edu | 302 G Talbot Laboratory, by appointment |

## General Information

### Online Course Platforms

We use Canvas for all communications, discussions, and as course material repository.

### Lectures

MWF 10-10.50 am, Engineering Hall 403B2. On occasion, asynchronous lectures will be pre-recorded in place of synchronous meetings. A dedicated announcement will be posted on Canvas. Recording will be posted in the corresponding Module in the course website.

Lecture recordings will be available to online student in Mediaspace right after each lecture.

### Course Synopsis

AE 480 HAT covers the fundamental aspects of hypersonic flows and aerothermodynamics of high-speed vehicles. We will explore the underlying phenomena of the aerothermal environment around a hypersonic aircraft, where extreme temperatures and heat loads, caused by air friction and shock waves, continuously challenge the performance of the vehicle.

### Course Outline

1. Introduction to hypersonic aerothermodynamics
2. Inviscid hypersonic flows
3. Hypersonic boundary layers
4. Basics of high temperature gas dynamics and thermochemical nonequilibrium flows
5. Re-entry aeromechanics

### Credits

3 undergraduate hours, 3 or 4 graduate hours.

### Prerequisites

AE 312 – Compressible Flows.

### Course discussions and Communications

We will use the *Discussions* section in Canvas for course discussions. You are encouraged to post your questions regarding class content, assignments, and exams, especially when you are struggling to understand a concept. Use Canvas for communicating with your instructor. Please limit the use of email communication to emergency situations only.

## Course Materials

### Recommended Course Materials

Course notes and handouts provided by the instructor.

### Recommended Textbooks

There is no required textbook for the present course.

The following textbooks are recommended as an integration to the course notes:
[1] J.D. Anderson, *Hypersonic and High-Temperature Gas Dynamics*
[2] C. Park, *Nonequilibrium Hypersonic Aerothermodynamics*
[3] J.J. Bertin, *Hypersonic Aerothermodynamics*

Other relevant reference books are:
[4] E. Josyula, *Hypersonic Nonequilibrium Flows: Fundamentals and Recent Advances*
[5] W. Hankey, *Re-entry Aerodynamics*

Supplementary references from the classical literature will be provided in Canvas.

## Homework & Exams

### Homework

There will be 5 homework assignments evenly distributed during the duration of the course. Homework will be posted on Canvas on predefined dates as indicated in the Course Schedule section below. Note that those may be subject to change, therefore it is your responsibility to keep track of any pertinent announcement during lectures and to check periodically for Syllabus updates or online announcements. You will usually have 1 week to complete your homework assignments.

*Submission guidelines*. Homework must be submitted in Canvas by the due date/time. Submit your homework as a single PDF file including all derivations, explanations, figures, data and any code that you have used to produce your solution. Start every problem on a fresh side of a page. If you handwrite your solutions and print off figures, you will need to scan everything into a single PDF file. If you use a typesetting program, such as LaTeX or MS Word, then save your file as a PDF. Canvas will allow unlimited submission attempts until the deadline, and no submission thereafter.

*Quality requirements*. Turn in neat and clean submissions that give all the formulae, details and information that are required to understand and grade your solution, including any code that you have used or created. Handwritten homework that are illegible will be assigned zero points. For each problem:

1. Briefly state the information given.
2. State the information to be found.
3. Include a schematic of the system that you are solving. Label the schematic with an appropriate coordinate system, flow velocity vectors, and other labels.
4. Write down the appropriate mathematical equations you are using to solve the problem.
5. Clearly state any of the assumptions that you are using for solving your problem.
6. Show the exact value of the variables that you are substituting into the equations.
7. Ensure consistent units are being used when substituting numerical values and that the number of significant figures are consistent with the data provided.
8. After completing the problem, pause, and think: "does my solution make physical sense?".
9. Place the answer in a box and label the important equations.

*Late policy*. Late homework will be accepted up to 24 hours after the due date/time. A 4% penalty will be applied per each delay hour and taken off your homework grade. The 24-hour deadline after the due date/time is a hard deadline. Because homework solutions are automatically posted in Canvas 24 hours after the assignment is due, no submission will be accepted after this hard deadline.

## Exams

Two midterm exams will be given. Anticipated dates for the exams are indicated in the Course Schedule section. Note that those may be subject to change, therefore it is your responsibility to keep track of any pertinent announcement during lectures and to check periodically for Syllabus updates or online announcements. The following guidelines apply to both midterm exams:

- **Midterm 1** will take place at **10–11 am**, **US Central Time**, on **Sep 27.**
- **Midterm 2** will take place at **10–11 am**, **US Central Time**, on **Nov 01.**
- Both midterm exams will be organized in two parts:
    - Part I – theory questions (20 min): closed notes and book, no calculator allowed.
    - Part II – problem solving (40 min): open notes and book, calculator allowed.

  The instructor/proctor will collect Part I of your exam before you start part II.
- The exam will be worth a total of 100 points. You will need to allocate your time wisely and use the number of points assigned to each problem as your guide.
- In order to get full credit on the problems, you must show all your work. Your partial credit might depend on it. No credit will be given without supporting material.
- Indicate units of your answers, when applicable, for full points.
- Turn in a neat and clean exam that gives all the formulae that you have used as well as details that are required for the grader to understand your solution.
- Exam will be comprehensive on the entire course material covered up to the exam date.
- Exam will be structured in two parts, a section on theory/conceptual questions and a problem-solving section.
- To prepare for the exam, you should thoroughly study your course notes, and review problems solved during homework assignments.
- If you are enrolled in the ONL section of the course, please make the necessary arrangements for the exams.

## Final Project

A final project will be an important part of this class and will allow you to deep dive in one or more of the topics covered in class, as well as to explore materials that is not covered during the course, but it is important to the field of hypersonic aerothermodynamics. You will work in teams of 2 to 4 members to carry out the project. Use the Discussions section in Canvas to create groups.

*Abstract.* Each group is required to prepare a 2-page abstract on a topic of interest that they intend to cover. The abstract should outline the project proposal with relevant references, should clearly identify objectives and what tools will be used to develop the project, and should provide a timeline with intermediate milestones to reach the objectives. The instructor will review the abstract to ensure that the topic and scope are appropriate.

*Project Report.* The main outcome of the project will be a 10-20 pages report that summarizes the findings and lessons learned of the study. The executive summary and references should be written in a style appropriate for submission to the *AIAA Journal*. Please consult https://www.aiaa.org/journal-authors/ for guidelines and templates. Use a single-spaced document written in 12-point font, Times New Roman. Make good-quality figures following the AIAA artwork guidelines. Eliminate all waste space from graphs and figures and between the parts of multipart figures. Limit figure and plot size to 3 1/4 in. wide by 3 1/2 in. high. Include a concise Contributions statement at the end of the Report.

*List of Topics.* Each group is encouraged to identify and develop a topic of their own interest. A few examples of project ideas are provided below:

- Design of a Hypersonic Shock Tube
- Numerical Simulations of the CHESS Plasmatron X Environment
- Development of a Non-Equilibrium Boundary Layer Solver
- Hypersonic CFD Simulations using the Eilmer Code
- Transport Properties of Reactive Air-Gas using Mutation++
- Equilibrium Chemistry Analysis for Titan Entry using Mutation++
- Ablative Material Simulations using PATO

- Nozzle Ablation Simulations using PATO
- Any topic of your choice. Be creative!

Consult with your instructor to develop the project idea. Your instructor will help you to find suitable resources and tools.

*Grading*. The final project is worth 100 pts. The final grade will be based on the quality of the report (40%), the originality of the project (20%), the correctness of the results and analysis (20%), and the commitment and contribution to the project (20%).

*Due Dates*. Due dates are indicated in the Course Schedule section and are also reported below:

- Form groups and communicate them to your instructor by **Sep 11**.
- Email project abstracts to your instructor in pdf form by **Oct 09**.
- Email final projects report to your instructor in pdf form by **Dec 8**.

### Grading Policy

We will observe the following grading scheme.

| | **3 hours** | **4 hours** |
|---|---|---|
| Homework | 25% | 20% |
| Midterm I | 20% | 15% |
| Midterm II | 20% | 15% |
| Final project | 35% | 30% |
| 4th Credit Assignment | | 20% |

| **Grade** | Percentile | **Grade** | Percentile | **Grade** | Percentile | **Grade** | Percentile | **Grade** | Percentile |
|---|---|---|---|---|---|---|---|---|---|
| **A+** | =>97 | **B+** | 87-90 | **C+** | 77-80 | **D+** | 67-70 | **F** | <60 |
| **A** | 93-97 | **B** | 83-87 | **C** | 73-77 | **D** | 63-67 | | |
| **A-** | 90-93 | **B-** | 80-83 | **C-** | 70-73 | **D-** | 60-63 | | |

The cutoffs in the above table *might* be lowered, but they will not be raised. Furthermore, they are strict. For example, a grade of 89.99% is a B+ and not an A-.

### Regrading Policy

Regrade of homework or exam will follow this process:

- You must wait 24 hours after receiving your returned item before contacting your instructor. During this time, please carefully consider what the dispute is and why you believe an error has been made.
- Requests must be made in Canvas, with rationale, and within 3 days of returned items. After 3 days no dispute will be considered.

## Academic Integrity

We abide by the Student Code of the University of Illinois at Urbana-Champaign.

## Sexual Misconduct Reporting Obligation

The University of Illinois is committed to combating sexual misconduct. Faculty and staff members are required to report any instances of sexual misconduct to the University's Title IX Office. In turn, an individual with the Title IX Office will provide information about rights and options, including accommodations, support services, the campus disciplinary process, and law enforcement options.

A list of the designated University employees who, as counselors, confidential advisors, and medical professionals, do not have this reporting responsibility and can maintain confidentiality, can be found here.

Other information about resources and reporting is available at wecare.illinois.edu.

### Religious Observances

Illinois law requires the University to reasonably accommodate its students' religious beliefs, observances, and practices in regard to admissions, class attendance, and the scheduling of examinations and work requirements. You should examine this syllabus at the beginning of the semester for potential conflicts between course deadlines and any of your religious observances. If a conflict exists, you should notify your instructor of the conflict and follow the procedure to request appropriate accommodations. This should be done in the first two weeks of classes.

### Disability Accommodations

To obtain disability-related academic adjustments and/or auxiliary aids, students with disabilities must contact the course instructor and the Disability Resources and Educational Services (DRES) as soon as possible. To contact DRES, you may visit 1207 S. Oak St., Champaign, call 333-4603, e-mail disability@illinois.edu or go to the DRES website.

### Family Educational Rights and Privacy Act (FERPA)

Any student who has suppressed their directory information pursuant to Family Educational Rights and Privacy Act (FERPA) should self-identify to the instructor to ensure protection of the privacy of their attendance in this course. More information on FERPA is available here.

### Belonging

A feeling of belonging and inclusion is critical to the success and health of our community. The Aerospace Engineering department has a committee called Aero’s Space to Belong. They offer office hours, one-on-one discussion, and a reporting process. If you experience conflict that undermines your or someone else’s feelings of belonging, please consider using these resources: https://aerospace.illinois.edu/diversity/reporting

### Respect and Growth in the Classroom

The effectiveness of our course is dependent upon each of us to create a safe and encouraging learning environment that allows for the open exchange of ideas while also ensuring equitable opportunities and respect for all of us. Everyone is expected to help establish and maintain an environment where students, staff, and faculty can contribute without fear of personal ridicule, or intolerant or offensive language. We ask everyone to be ready to learn and grow in your respect and understanding of others, in addition to your understanding of the course material.

### Anti-Racism and Inclusivity

The Grainger College of Engineering is committed to the creation of an anti-racist, inclusive community that welcomes diversity along a number of dimensions, including, but not limited to, race, ethnicity and national origins, gender and gender identity, sexuality, disability status, class, age, or religious beliefs. The College recognizes that we are learning together in the midst of the Black Lives Matter movement, that Black, Hispanic, and Indigenous voices and contributions have largely either been excluded from, or not recognized in, science and engineering, and that both overt racism and micro-aggressions threaten the well-being of our students and our university community.

*It is the instructor’s intent that students from all diverse backgrounds and perspectives be well served by this course, that students’ learning needs be addressed both in and out of class, and that the diversity that students bring to this* *class be viewed as a resource, strength, and benefit. It is the instructor's intent to present materials that are respectful of diversity, gender, sexuality, disability, age, socioeconomic status, ethnicity, race, and culture. Your suggestions are encouraged and appreciated. Please let the instructor know of ways to improve the effectiveness of the course for you personally or for other students.*

## COVID-19

If you feel ill or are unable to come to class or complete class assignments due to issues related to COVID-19, including but not limited to testing positive yourself, feeling ill, caring for a family member with COVID-19, or having unexpected child-care obligations, you should contact your instructor immediately, and you are encouraged to copy your academic advisor.

## Extra Resources to Succeed

### Counseling Center

Counseling Center services are designed to help students address many of the academic, relational, social, and emotional concerns they face. The Counseling Center provides a same-day appointment system. To schedule a same-day, confidential appointment please call 217-333-3704 any time after 7:50 a.m., Monday through Friday or go to the Counseling Center website.

### Health Center

The McKinley Health Center provides medical services to students University of Illinois at Urbana-Champaign. The Health Service Fee, which is paid as part of your enrollment, provides the funds to prepay many of your health care needs. To schedule appointments please call 217-333-2700, Monday through Friday, 8 a.m. to 5 p.m. or go to the McKinley website. For ambulance or emergency situations dial: 911 (from a campus phone: 9-911).

### Office of the Dean of Students

The Office of the Dean of Students implements a variety of programs and services to assist and support students in achieving academic and personal success. The Office provides important educational and developmental opportunities, serves as student advocates, empowers students to be successful, and promotes students' rights and responsibilities. For more information, please visit the Office of the Dean of Students website.

### Center for Academic Resources in Engineering

The Center for Academic Resources in Engineering (CARE) enhances the learning experience for all undergraduate engineering students through academic support, enhancing collaborative learning opportunities, and providing positive influence through peer mentoring. For more information, please visit the CARE website.

## Course Schedule[1]

| Week # | Mon | Tue | Wed | Thu | Fri |
|---|---|---|---|---|---|
| 1 | Aug-21<br>Instruction Begins | Aug-22 | Aug-23 | Aug-24 | Aug-25 |
| 2 | Aug-28 | Aug-29 | Aug-30 | Aug-31 | **Sep-01**<br>**Homework 1 Assigned** |
| 3 | Sep-04<br>Labor Day – No Class | Sep-05 | Sep-06 | Sep-07 | **Sep-08**<br>**Homework 1 Due** |
| 4 | **Sep-11**<br>**Project Groups** | Sep-12 | Sep-13 | Sep-14 | **Sep-15**<br>**4th Credit – Part 1 Due** |
| 5 | **Sep-18**<br>**Homework 2 Assigned** | Sep-19 | Sep-20 | Sep-21 | Sep-22 |
| 6 | **Sep-25**<br>**Homework 2 Due** | Sep-26 | **Sep-27**<br>**Midterm 1** | Sep-28 | Sep-29 |
| 7 | Oct-02 | Oct-03 | Oct-04 | Oct-05 | Oct-06 |
| 8 | **Oct-09**<br>**Project Abstracts** | Oct-10 | Oct-11 | Oct-12 | **Oct-13**<br>**Homework 3 Assigned** |
| 9 | Oct-16 | Oct-17 | Oct-18 | Oct-19 | **Oct-20**<br>**Homework 3 Due** |
| 10 | Oct-23 | Oct-24 | Oct-25 | Oct-26 | **Oct-27**<br>**4th Credit – Part 2 Due** |
| 11 | **Oct-30**<br>**Homework 4 Assigned** | Oct-31 | **Nov-01**<br>**Midterm 2** | Nov-02 | Nov-03 |
| 12 | **Nov-06**<br>**Homework 4 Due** | Nov-07 | Nov-08 | Nov-09 | Nov-10 |
| 13 | Nov-13 | Nov-14 | **Nov-15**<br>**Homework 5 Assigned** | Nov-16 | **Nov-17**<br>**4th Credit – Part 3 Due** |
| 14 | Nov-20<br>Break | Nov-21<br>Break | Nov-22<br>Break | Nov-23<br>Holiday | Nov-24<br>Holiday |
| 15 | Nov-27 | Nov-28 | Nov-29 | Nov-30 | **Dec-01**<br>**Homework 5 Due** |
| 16 | **Dec-04**<br>**4th credit – Part 4 Due** | Dec-05 | Dec-06<br>Instruction Ends | Dec-07<br>Reading Day | **Dec-08**<br>**Final Project Reports** |
| 17 | Dec-11 | Dec-12 | Dec-13 | Dec-14 | Dec-15 |

[1]Consider this a tentative schedule that will be updated during the course.

## Course Schedule

| Week # | Lecture | Homework |
|---|---|---|
| 1 | Module 1: Introduction to hypersonic aerothermodynamics | Homework 1 |
| 2 | Module 2: Inviscid hypersonic flows<br>• Compressible flows in the hypersonic limit | Homework 2 |
| 3 | Module 2: Inviscid hypersonic flows<br>• Straight Newtonian theory<br>• Modified Newtonian theory | |
| 4 | Module 2: Inviscid hypersonic flows<br>• Combined limit $M_\infty \to \infty$ and $\gamma \to 1$<br>• Physical significance of the density ratio $\varepsilon$<br>• Taylor-Maccoll theory | |
| 5 | Module 2: Inviscid hypersonic flows<br>• Small disturbance theory<br>• Mach number independence principle<br>• Hypersonic similarity<br>• Vorticity | |
| 6 | Module 3: Hypersonic boundary layers<br>• Intro to viscous and rarefied flow effects<br>• The role of flight altitude<br>• Recovery factor<br>• Derivation of boundary layer equations | Homework 3 |
| 7 | Module 3: Hypersonic boundary layers<br>• Crocco-Busemann equation<br>• Stanton number and skin friction coefficient<br>• Self-similar solutions | |
| 8 | Module 3: Hypersonic boundary layers<br>• Self-similar solutions, contd.<br>• Reynolds analogy<br>• Stagnation-point hypersonic boundary layers | |
| 9 | Module 3: Hypersonic boundary layers<br>• Stagnation-point heat transfer<br>• Aerodynamics heating processes | |
| 10 | Module 4: High-Speed Thermochemical Effects<br>• Intro to high-speed thermochemistry<br>• Chemically reactive flows<br>• Thermochemical equilibrium | Homework 4 |
| 11 | Module 4: High-Speed Thermochemical Effects<br>• Vibrational excitation<br>• Equilibrium inviscid hypersonic flows<br>• Plasma sheath | |
| 12 | Module 4: High-Speed Thermochemical Effects<br>• Nonequilibrium inviscid hypersonic flows | |
| 13 | Module 5: Re-entry aeromechanics<br>• Intro and general aeromechanics considerations | Homework 5 |
| 14 | Holyday | |
| 15 | Module 5: Re-entry aeromechanics<br>• Ballistic entry<br>• Reentry heating | |
| 16 | Module 5: Re-entry aeromechanics<br>• Thermal protection systems classes and sizing | |

## 4th Credit Hour Assignment

### Assignment

Each 4th credit student is required to create original homework problems, based on the material covered during the course. Each student shall create 3 homework problems for each of the main sections of the course:

- Part 1 – homework problems on Inviscid hypersonic flows
- Part 2 – homework problems on Hypersonic boundary layers
- Part 3 – homework problems on High temperature gas dynamics and thermochemical nonequilibrium flows
- Part 4 – homework problems on Re-entry aeromechanics

for a total of 12 homework problems. Aim for the same level of difficulty you might find on an assigned homework or exam. Be original. You are encouraged to create homework problems that require coding in python or Matlab. For each submission, provide a Word or *LaTeX* document with the problem descriptions and solutions. Submissions must be made by uploading problem files and any code file in Canvas.

### Grading

Each part is graded individually and is worth 100 pts. The final grade will be the arithmetic mean of the grades of each part. Points will be assigned based on creativity and originality (50%), on the right level of difficulty of the full problem set (20%), on the correctness of the solution (20%), on the presentation of the problems' description and solution in a neat and clean fashion (10%).

### Due dates

Due dates are indicated in the Course Schedule section. Note that those may be subject to change, therefore it is your responsibility to keep track of any pertinent announcement during lectures and to check periodically for Syllabus updates or announcements in Canvas. Submissions shall be made no later than 5 pm on the due date.

## Detailed Outline

1. Introduction to Hypersonic Aerothermodynamics
    1.1. Definition of Hypersonic Flow
    1.2. Some Historical Landmarks and Considerations
    1.3. Classes of Hypersonic Systems
    1.4. The hypersonic environment

*Objective: introduce the topic of hypersonic flows and develop a basic understanding of the main challenges*

2. Inviscid Hypersonic Flows
    2.1. The Hypersonic Limit for Shock Wave Jump Conditions
    2.2. The Hypersonic Limit for Expansion Waves
    2.3. Newtonian Theory of Hypersonic Flows
    2.4. The Combined Limit $M_\infty \to \infty$ and $\gamma \to 1$
    2.5. Physical Significance of the Density Ratio $\varepsilon$
    2.6. Taylor-Maccoll theory for Hypersonic Flows around Slender Bodies
    2.7. Mach Number Independence Principle
    2.8. Small Disturbance Theory of Hypersonic Flows
    2.9. Inviscid Hypersonic Flows Around Blunt Bodies

*Objective: learn to analyze high Mach number flows from a pure fluid dynamics perspective*

3. Viscous Hypersonic Flows
    3.1. Role of Flight Altitude
    3.2. Compressible Laminar Boundary Layers

*Objective: learn to analyze aerothermal viscous effects in hypersonic flows*

4. High-Speed Thermochemical Effects
    4.1. The Role of Thermochemical Effects in Hypersonics
    4.2. Basic Concepts of Thermodynamics and Physical Chemistry
    4.3. High-temperature Equilibrium Flows
    4.4. High-temperature Non-equilibrium Flows
    4.5. Basic Concepts of Radiative Heat Transfer

*Objective: develop a basic knowledge of high temperature chemical phenomena in hypersonic flows*

5. Re-entry aeromechanics
    5.1. General Considerations
    5.2. Ballistic Re-entry Aeromechanics
    5.3. Re-entry Heating

*Objective: learn properties of and analysis approach to different types of entry trajectories*

*The instructor reserves the right to make any changes to the syllabus and course content that he considers academically advisable. Such changes, if any, will be announced in class and implemented in a new version of the syllabus posted in the course website. Please note that is responsibility of each student to attend the class, visit the course website and keep track of the proceedings.*