ME 530 Advanced Heat Transfer
WINTER 2019

SYLLABUS – UPDATED 01/07/19

Instructor:	Rohini Bala Chandran Assistant Professor of Mechanical Engineering Office: 3455 G.G. Brown Building Email: rbchan@umich.edu Prof. Bala Chandran will teach the majority of the classes. She is responsible for course design, lectures, homework, midterm exam, and the final project. She oversees the preparation of the solutions, the grading of the work, and addresses any questions about homework and assigns final course grades.
Meeting time:	**Lectures:** Tu & Th 9.00 AM – 10.30 AM, 1690 Beyster **Office Hours:** Tu & Th: 10.30 AM – 11.30 AM, 3455 G.G.Brown Email instructor to set up appointments outside of the times presented here
Course Description:	**Advanced Heat Transfer (ME 530)** is intended as a first graduate-level introduction to the three basic modes of heat transfer — conduction, convection and radiation. It is a 3-credit, core graduate heat transfer course in the ME department. This course is open to students from all areas of engineering and applied sciences, although an undergraduate background in heat transfer will be assumed. We will present detailed discussions and first-principles derivations of pertinent governing equations, analytical and computational problem solving techniques, and the process of developing rational approximations to solve heat transfer problems. This course will emphasize more on the topics of conduction and radiation as compared to convection. Radiative heat transfer, which is often treated inadequately in typical undergraduate classes, will be specifically highlighted with applications to emerging energy conversion and storage technologies. In this comprehensive heat transfer introduction course, students will be asked to work on a final project using heat transfer analysis and design for a real-life engineering/research problem of their own choice.
Course Scope:	Topics to be covered *include but not limited* to: conservation laws and the energy transport equation; conduction heat transfer – one-dimensional, two-dimensional, steady-state and transient systems; laminar convection; heat-exchanger design; fundamentals of radiative energy transport, radiative exchange between surfaces, radiative heat-transfer in absorbing-emitting-scattering media; introduction to Monte Carlo techniques; heat- and mass-transfer analogies; advanced multimode heat-transfer problems.
Course Objectives:	1. To enhance the understanding of heat transfer processes and their relevance to industrial problems 2. To understand the derivation and physical meaning of energy transport equations 3. To strengthen analytical, numerical and computational skills to solve complex heat transfer problems 4. To provide experience in treating multimode heat transfer effects and in solving realistic engineering problems

Prerequisites:

- ME 335 (undergraduate heat transfer) or equivalent; undergraduate exposure to thermodynamics and fluid mechanics.
- Undergraduate mathematical preparation including vector calculus, ordinary and linear partial differential equations solved via separation of variables and Fourier series will be helpful.
- Moderate proficiency in MATLAB (or other programming languages such as PYTHON, FORTRAN, C, C++), including plotting, conditional statements, loops, and engineering computations with scalars and vectors.

Course website: https://umich.instructure.com/courses/279823

Please be sure to allow alerts to Canvas notifications from ME530 Section 001. All course related announcements, homework assignments, supplementary handouts, HW and exam solutions, and lecture notes will be posted on Canvas.

Textbook: Fundamentals of Heat and Mass Transfer (7th Edition), *Theodore L. Bergman, Adrienne S. Lavine, Frank P. Incropera, David P. DeWitt* (Wiley)
This textbook will serve as a good first resource for information covered in this class. Any edition of the textbook is OK. See page 5 of the syllabus for additional suggested readings and reference materials.

Grading: *Homework: 35%* of the final grade
Take home exam: 25% of the final grade
Term Project & Report: 40% of the final grade
For the overall course, a simple grading scheme will be applied; all cumulative scores will be computed to two decimal places and will be rounded up to the nearest whole number.

A+	97-100	A	93-96	A-	90-92
B+	87-89	B	83-86	B-	80-82
C+	77-79	C	73-76	C-	70-72
D+	67-69	D	65-66	E/F	Below 65

Homework:

- Roughly 4 HWs will be assigned over the course of the semester;
- HWs will be assigned on Thursdays; ~ 2 weeks to solve each HW. Check the class schedule (Pg. 7) for the specific due dates for each HW assignment.
- HWs will involve analytical and/or computational problem-solving techniques. For the computational assignments, you will be expected to develop your own code using your choice of a programming language MATLAB/C/C++/Python/Fortran.
- Specific instructions will be provided on Canvas for the submission of each HW and students are responsible to keep track of them.
- While course participants are encouraged to discuss, collaborate and learn from each other, HW submissions need to reflect a student's individual work and understanding.
- HWs will be graded on a somewhat simplified scheme that prioritizes the methodology and the process more than the final answer. Generally, if sufficient effort is displayed in solving a problem by adopting the correct approach, and the problem has been completely solved, you will be awarded a 100% grade for that problem. Should the solution be incomplete, with the correct approach, you will be given 75% for that problem. If neither the approach nor the solution is appropriate, but the student has made a partial attempt, you will get 25% on a problem. A grossly insufficient effort (or no homework) will receive 0% .

Take-home Exam

- The take-home exam will be distributed in class on **Thursday** and will be **due on the following Tuesday** in class.
- This exam is open-book and you can access any resources (books, notes, assignments, papers, Google, etc.).
- The honor code must be strictly observed, i.e., you need to work independently on the exam problems without any communication/help from other course participants and/or third parties.
- The take-home exam will be graded similar to the HWs.

Final Term Project:

The final event of ME 530 is a term project carried out by a group of *3-4* students taking the course. In the project, you are to perform quantitative modeling and analysis of an engineering system/product of your interest. The project topic should be initiated by the students -- it can be adopted from the students' research topics and/or based on your own curiosities and interests. The instructor will also willingly consult with students that need additional help to come up with project topics. If there is significant interest in developing a working prototype/design an experiment involving a heat-transfer problem, that can also be considered as a viable project topic but the team has to consult with the instructor early on in the semester.

Required Steps: (a) Pick up a particular engineering system (e.g., additive manufacturing, solar-thermal energy conversion and storage systems, thermal design challenges in batteries, electronic devices and sensors, thermal meteorology instrument, thermal surgical tool, and so on) (b) Define heat a transfer problem for the selected system in connection to a particular application (e.g. (c) Develop a heat transfer model for the selected system (d) Perform quantitative analysis using analytical/numerical/computational technique to evaluate the performance of the selected system. (e) Discuss the significance of your analysis.

Because the final term project amounts to 40% of the final grade, periodic milestones have been designed through the course of the semester to keep the teams on track towards successfully completing the term project. Refer to the class schedule on Pg. for specific milestone deadlines.

- ***Team list*** *(3%)*
  - Form teams of 3, maximum 4 students; submit team lists to the instructor via email
- ***1-page*** **term** ***project proposal (12%)***
  - Include title, team members, project objectives, and a key figure
  - 12-point font size, single column, single line spacing
- ***Progress report (25%)***
  - Include problem statement/project objectives, proposed approach including key governing equations, task list with tentative plan for accomplishing tasks, and preliminary results if any
  - 12-point font size, single column, single line spacing, maximum 4 pages
- ***Final project presentations*** **(35%)**
  - 15-20 min group presentations of your project
  - Quality of presentation, overall team effort, clarity of approach selection and implementation, rational approximations applied, results explanation and discussion, oral Q/A performance of the team members and individual contributions are some of the evaluation criteria
- ***Final project report (25%)***
  - Build on the progress report; include Introduction & Background, Project objectives, Results and Discussion, Conclusions
  - 12-point font size, single column, single line spacing, maximum 8 pages

Honor code: All students participating in ME 530 are presumed to be decent, honest, and to abide by reasonable standards of conduct. All course policies are governed by the UM College of Engineering honor code. In summary, the honor code states that "No member of the UM community shall take unfair advantage of any other member of the UM community". For more information: https://ossa.engin.umich.edu/honor-council/

Late Policy, Regrades, and Others:

- Late HWs/Exams/Term project milestones will NOT be accepted unless there is a proven case of a personal medical condition or if you will be representing UM at any science/engineering/art competition.
- Students feeling that homework was graded inaccurately should request a regrade in writing, on paper, and in person to Prof. Bala Chandran. Requests made via email will not be considered. This request should include the original homework, a description of the item in question and why it was graded incorrectly. Requests must be made within 10 business days from when the homework is returned to you.
- Students are responsible for diligently monitoring their grades on the class website and reporting any discrepancies within 10 business days of the grades being posted.

Special accommodation: If you think you need an accommodation for a disability, please let me know at your earliest convenience. Some aspects of this course, the assignments, exams, and the way the course is usually taught may be modified to facilitate your participation and progress. As soon as you make me aware of your needs, we can work with the Services for Students with Disabilities (SSD) office to help us determine appropriate academic accommodations. SSD (734-763-3000; http://ssd.umich.edu) typically recommends accommodations through a Verified Individualized Services and Accommodations (VISA) form. Any information you provide is private and confidential and will be treated as such.

Student Support Services: As a student you may experience a range of issues that can cause barriers to learning, such as strained relationships, increased anxiety, alcohol/drug problems, feeling down, difficulty concentrating and/or lack of motivation. These mental health concerns or stressful events may lead to diminished academic performance or reduce a student's ability to participate in daily activities. The University of Michigan is committed to advancing the mental health and well-being of its students. If you or someone you know is feeling overwhelmed, depressed, and/or in need of support, services are available. You can learn more about the broad range of confidential mental health services available on campus via http://umich. edu/~mhealth/

ME 530: Supplementary Reference Resources

Due to the wide range of topics that will be discussed, a number of classical textbooks can serve as excellent resources for this class is presented below with brief descriptions; those marked with an **asterisk** will be the most relevant for our discussion.

General

- Lienhard IV and Lienhard V, *A Heat Transfer Textbook (2012)*. Free introductory heat transfer text available free online at http://web.mit.edu/lienhard/www/ahtt.html
- *Bird, R.B. Stewart, W.E. and E.N. Lightfoot, *Transport Phenomena*, John Wiley (1960). A comprehensive treatment of momentum, heat and mass transfer and a classic. Extensive treatment of conservation equations.
- *Nellis and Klein, Heat Transfer (2009). Introductory text including examples with Matlab, Maple, and EES.

Conduction/Diffusion

- *Arpaci, V.S., *Conduction Heat Transfer*, Addison-Wesley (1966). Great mathematical foundation for conductive heat transfer. Book is currently out of print but online copies seem to be available for downloading
- *Ozisik, M.N., *Heat Conduction*, John Wiley (1984). Extensive discussion of analytical methods suitable for conduction problems. Many applications to different geometries and thermal conditions.
- Carslaw, H.S. and J.C. Jaeger, *Conduction of Heat in Solids*, Oxford University Press (1959). For many years, the definitive work on conduction heat transfer analysis. Mathematical developments terse, but results presented for many geometries and conditions.

Convection

- *Kays, W.M. and M.E. Crawford, *Convective Heat and Mass Transfer*, McGraw-Hill (1993). Excellent treatment of laminar and turbulent single phase forced convection.
- Bejan, A., *Convection Heat Transfer*, John Wiley (1984). Emphasis on appropriate scaling parameters and natural convection.

Radiation

- *Modest, M. F., *Radiative Heat Transfer*, Mc-Graw Hill (1993). Radiation heat transfer text available free online at http://www.sciencedirect.com/science/book/9780123869449. We will use this textbook a lot when when covering radiative heat transfer.
- Siegel, R. and J.R. Howell, *Thermal Radiation Heat Transfer*, Hemisphere (1992). A very detailed and excellent treatment of radiation – a classic.
- Bohren, C.F, and Hufman, D.R., 1984, *Absorption and Scattering of Light by Small Particles*, John Wiley & Sons.

Special Topics

- *E. Kreyszig, *Advanced Engineering Mathematics*, Wiley, 1988. Excellent general reference for most mathematical analysis methods.
- Carey, V.P., Liquid-Vapor Phase-Change Phenomena, Hemisphere (1992). Good treatment of boiling and condensation.
- Minkowycz, W.J., Sparrow, E.M., Schneider, G.E., Pletcher, P.H. (Eds.), *Handbook of Numerical Heat Transfer*, John Wiley (1998). Reference source for numerical methods
- Press, W.H., Flannery, B.P., Teukolsky, S.A. and Vetterling, W.T., *Numerical Recipes*, Cambridge (1989). Self-explanatory name – useful book.

ME 530: Tentative Schedule, Winter 2019

Week	Day and Date	Topics	HW (due date)	Term project/Exam
1	Th Jan 10	Lecture cancelled because Rohini is attending an energy storage workshop organized by industry, academia and the Department of Energy on Jan 9th and 10th.		
2	Tu Jan 15 Th Jan 17	Introduction and syllabus survey; conservation equations; general heat conduction equation, Dimensionless numbers, 1-D steady-state equation		
3	Tu Jan 22 Th Jan 24	1-D steady-state heat conduction, 1-D fins 2-D conduction, method of separation of variables	HW 1 **(01/31)**	
4	Tu Jan 29 Th Jan 30	2-D conduction separation of variables, superposition Unsteady/transient conduction equation, analytical solution techniques, Laplace transform solutions for lumped capacitance problems		
5	Tu Feb 5 Th Feb 7	Unsteady/transient conduction: numerical and computational techniques (finite difference, finite volume) to solve conduction problems	HW 2 **(02/21)**	Term project teams formed; email notification to instructor by **02/05, 8 PM**
6	Tu Feb 12 Th Feb 14	Conduction continued Convection introduction, conservation equations derivation; laminar boundary layer equations		
7	Tu Feb 19 Th Feb 21	External convective flows: integral solutions Internal convective flows and correlations		1-page term project proposal **02/19, 8 PM**
8	Tu Feb 26, Th Feb 28	Introduction to heat exchangers LMTD and e-NTU methods for heat exchanger design	HW 3 **(03/14)**	Comments on project proposal posted by **02/28**
9	Tu Mar 5 Th Mar 7	*Spring Break: No lecture*		
10	Tu Mar 12 Th Mar 14	Radiation fundamentals; surface optical properties, View Factors, radiative exchange between surfaces		
11	Tu Mar 19 Th Mar 21	Gray-diffuse surface radiation; Semi-gray surfaces Method of radiosity; Monte Carlo method (Part I) for surface radiation exchange		4-page progress report on term project due on **03/18, 8 PM** Take-home exam assigned on **03/21**
12	Tu Mar 26 Th Mar 28	Monte Carlo method (Part I) for surface radiation exchange; Radiative Transport Equation (RTE)	HW 4 **(04/16)**	Take-home exam due on **03/26**
13	Tu Apr 2 Th Apr 4	RTE approximations in participating media and solution techniques		
14	Tu Apr 9 Th Apr 10	Monte Carlo method (Part II) for solving the RTE in participating media		

15	Tu Apr 16 Th Apr 18	Radiation contd. Review and special topics discussion		
16	Tu Apr 23	*No lecture, students work on final project*		
Final Project Presentations: April 25th and 26th , Time and Venue TBD **Final Project Report due on April 28th, 8 PM**				