

2.51 INTERMEDIATE HEAT AND MASS TRANSFER

COURSE INFORMATION Fall Term 2006

1 CREDIT AND CONTENT

Course 2.51 is a 12-unit subject, serving as the Mechanical Engineering department's advanced undergraduate course in heat and mass transfer. The prerequisites for this course are undergraduate courses in thermodynamics and fluid mechanics, specifically 2.005 and 2.006 or their equivalents.

Topics to be covered include: unsteady heat conduction in one or more dimensions, steady conduction in multidimensional configurations, numerical simulation of conduction; forced convection in laminar and turbulent flows; natural convection in internal and external configurations; heat transfer during condensation and boiling; mass transfer at low rates, evaporation; thermal radiation, black bodies, grey radiation networks, spectral and solar radiation. Problems and examples will emphasize modelling of complex systems drawn from manufacturing, electronics, consumer products, and energy systems.

2 CLASSES

LECTURES: Tuesdays and Thursdays from 11:00 am to 12:30 pm in Room 1-150

LECTURER: Professor Borivoje Mikic, Room 3-166, ×32242, mikic@mit.edu

TA: Omar Roushdy, Room 41-203, omarhar@mit.edu

RECITATIONS: 1 hour recitation to be announced

TEXTBOOK: *A Heat Transfer Textbook*, 3/e, by Lienhard and Lienhard (2005). *Free* in pdf format at: <http://web.mit.edu/lienhard/www/ahtt.html>. Paperback copies are also available for purchase.

3 EXAMS AND GRADING

The grade will be based on two midterm quizzes (40%), homework and class participation (25%), and a final exam (35%). The exams will be open book unless otherwise announced. They will cover material from the lectures and the homeworks.

The exam dates are as follow:

QUIZ #1: October 12 (Thursday), 11:00 am - 12:30 pm, Room 1-150

QUIZ #2: November 16 (Thursday), 11:00 am - 12:30 pm, Room 1-150

FINAL EXAM: December, time and place to be announced (3 hrs)

HOMEWORK PROBLEMS

Homework assignments paralleling the lectures will be distributed. These problems will apply the material covered in lectures and are essential to learning that material. They will involve theory, modelling, and design exercises. It is important that you work the problems yourself, even if you have access to old solutions.

RESERVED BOOKS IN BARKER LIBRARY

- J.H. Lienhard and J.H. Lienhard, *A Heat Transfer Textbook*, 3/e. Phlogiston Press, 2006.
- A.F. Mills, *Basic Heat and Mass Transfer*, 2/e. Prentice-Hall, 1999.
- Y.A. Çengel, *Heat Transfer: A Practical Approach*, 2/e. McGraw-Hill, 2003.
- H.D. Baehr and K. Stephan, *Heat and Mass Transfer*. Springer-Verlag, 1998.
- *Partial Differential Equation Toolbox User's Guide*. Mathworks, Inc., 1995.

4 CONDUCTION SIMULATION AND COMPUTATIONAL RESOURCES

The course will spend a week or so on numerical simulation of heat-conduction. The simulation software to be used is Matlab's PDEToolbox, which has a graphical-user-interface and performs finite-element analysis of two-dimensional time-dependent partial differential equations. The emphasis will be on modelling heat flow in complex geometries or with complex boundary conditions, rather than on numerical methods *per se*.

Matlab and PDEToolbox are on Athena or the ME Computer Cluster (Room 3-462). Both include online documentation. Manuals for each package are available in the Athena public clusters or from The MathWorks, Inc.

Other useful packages on Athena or the ME Computer Cluster include Maple and MathCAD. You are encouraged to apply them in the solution of homework problems. In constructing any numerical solution, you should be conscious of the model you assume, the simulation steps used by the code, and the property data employed (especially when temperature-dependent properties are involved). If you use software in the solution of homework, you must document your calculations clearly.

5 LECTURE SCHEDULE

LECTURE	DATE [†]	TOPIC	READING [‡]	HMWK DUE [†]
1	Sept 7	Modes of heat transfer	Chpt. 1	
2	Sept 12	CONDUCTION: Resistances; Energy equation	Chpt. 2	
3	Sept 14	Energy equation, Biot number	§§4.1-4.4	
4	Sept 19	Fins	§4.5	#1
5	Sept 21	Lumped capacity	§1.3, §§5.1-5.2	
6	Sept 26	Transient conduction	§§5.3-5.5	
7	Sept 28	Semi-infinite bodies	§5.6	#2
8	Oct 3	Multidimensional conduction	§§5.7-5.8	
9	Oct 5	Numerical simulation <i>in Room 1-115</i>	Handout	#3
*	Oct 10	<i>No Class (Columbus Day)</i>		
🍷	Oct 12	Quiz 1 (lectures 1-8)		
10	Oct 17	CONVECTION Conservation equations	§§6.1-6.4	
11	Oct 19	Laminar boundary layers	§§6.5-6.6	
12	Oct 24	Integral methods		
13	Oct 26	Internal flows	§§7.1-7.2	#4

[†]Dates and coverage may vary.

[‡]Readings are from *A Heat Transfer Textbook*, 3/e, v.1.2

LECTURE	DATE	TOPIC	READING	HMWK DUE
14	Oct 31	Turbulence	§§6.8-6.9, §7.3	
15	Nov 2	Turbulence, noncircular ducts, crossflows	§§7.4-7.6	
16	Nov 7	Natural convection	§§8.1-8.4	#5
17	Nov 9	Condensation	§8.5, §9.9	
18	Nov 14	MASS TRANSFER Mixtures, diffusion	§§11.1-11.3	#6
☛	Nov 16	Quiz 2 (lectures 10-17)		
19	Nov 21	Species conservation Analogy to heat transfer	§§11.5-11.6	
*	Nov 23	<i>No Class (Thanksgiving Day)</i>		
20	Nov 28	Evaporative cooling	§11.9	
21	Nov 30	RADIATION Black bodies	§1.3, §§10.1-10.2	#7
22	Dec 5	View factors	§10.3	
23	Dec 7	Gray body networks	§§10.4	
☛	Dec 9	<i>Homework #8 due by end of day</i>		#8
24	Dec 12	Spectral surfaces Solar radiation	§§10.5-10.6, handout	
☛	Dec	Final Exam (Comprehensive)		

6 PHYSICAL PROPERTIES & SI UNITS

Whenever assigning property data in a heat transfer problem, bear in mind that many properties (especially liquid viscosity) are very sensitive to temperature changes. Pressure variations often have less impact on transport properties, although they can significantly alter thermodynamic properties such as the density of gases and liquid boiling points. Pressure is often important in phase change processes.

The thermal conductivity of solids can vary significantly with: alloying, processing, density or compaction, and water content. For example, the conductivity of pure iron is 80 W/m·K, of 1.0% carbon steel is 43 W/m·K, and of 304 stainless steel is 14 W/m·K, each at 20°C.

A few of the many sources of property data are:

1. NIST Chemistry Webbook: <http://webbook.nist.gov/chemistry/fluid/>.
Thermophysical properties for a wide range of industrially important fluids are available using your browser. These are calculated over a user-specified range using up-to-date, high accuracy models for fluid properties.
2. **Thermophysical Properties of Matter**, edited by Y.S. Touloukian, 14 volumes, 1970–1978 (Purdue University, West Lafayette, IN). TA418.52.P985 REF
An enormous compilation of property data for a broad range of substances. Includes k , c_p , μ , α , as well as radiative properties and thermal expansion coefficients.
3. **Thermal Conductivity of the Elements: A Comprehensive Review**, C.Y. Ho, R.W. Powell, and P.E. Liley, *J. Phys. Chem. Ref. Data*, vol. 3, supp. 1, 1974. QC321.H6 REF
The title says it all. Published in book format; includes only pure elements.
4. **The Properties of Gases and Liquids**, by B.E. Poling, J.M. Prausnitz, and J.P. O'Connell, 5th ed., 2001 (McGraw-Hill, NYC) TP242.R357 2001 Science REF
Contains semiempirical equations for estimating thermodynamic & transport properties of pure substances and mixtures. A particularly good source for organics.

Compilations of property data are published by many scientific and commercial organizations, including the International Union of Pure and Applied Chemistry (IUPAC), the American Society for Metals (ASM), and the National Institute of Standards (NIST), and the International Association for the Properties of Water and Steam (**IAPWS**).

Table 1: Some Physical Constants

2002 **CODATA** with (1σ) uncertainty

Avogadro's number, N_A	6.0221415 (10) $\times 10^{26}$	molecules/kmol
Boltzmann's constant, k_B	1.3806505 (24) $\times 10^{-23}$	J/K
Ideal gas constant, R°	8314.472 (15)	J/kmol·K
Speed of light in vacuum, c	299,792,458 (0)	m/s
Standard acceleration of gravity, g	9.80665 (0)	m/s ²
Stefan-Boltzmann constant, σ	5.670400 (40) $\times 10^{-8}$	W/m ² K ⁴

Table 2: Selected Conversion Factors

<u>Dimension</u>	<u>SI</u>	=	<u>multiplier</u>	×	<u>Other Unit</u>
Density	kg/m ³	=	16.018	×	lbm/ft ³
	kg/m ³	=	10 ³	×	g/cm ³
Diffusivity (α, ν, D)	m ² /s	=	0.092903	×	ft ² /s
	m ² /s	=	10 ⁻⁶	×	centistokes
Energy	J	=	1055.04	×	Btu ^a
	J	=	4.1868	×	cal ^b
Flow rate	m ³ /s	=	6.3090×10 ⁻⁵	×	gal/min (gpm)
	m ³ /s	=	4.7195×10 ⁻⁴	×	ft ³ /min (cfm)
Heat flux	W/m ²	=	3.154	×	Btu/hr·ft ²
Heat transfer coefficient	W/m ² K	=	5.6786	×	Btu/hr·ft ² °F
Length	m	=	0.0254	×	inches
	m	=	0.3048	×	feet
Power	W	=	0.022597	×	ft·lbf/min
	W	=	0.29307	×	Btu/hr
	W	=	745.700	×	hp
Pressure	Pa	=	248.8	×	inH ₂ O (@60°F)
	Pa	=	6894.8	×	psi
	Pa	=	101325	×	atm
Specific heat capacity	J/kg·K	=	4186.9	×	Btu/lbm·°F
	J/kg·K	=	4186.8	×	cal/g·°C
Temperature	K	=	5/9	×	°R
	K	=	°C + 273.15		
	K	=	(°F + 459.67)/1.8		
Thermal conductivity	W/m·K	=	1.7307	×	Btu/hr·ft°F
	W/m·K	=	418.68	×	cal/s·cm°C
Viscosity (dynamic)	Pa·s	=	10 ⁻³	×	centipoise
	Pa·s	=	1.4881	×	lbm/ft·s
	Pa·s	=	47.8803	×	lbf·s/ft ²

^a The British thermal unit, originally defined as the heat that raises 1 lbm of water 1°F, has several values that depend mainly on the initial temperature of the water warmed. The above is the International Table (*i.e.*, steam table) Btu. A “mean” Btu of 1055.87 J is also common. Related quantities are: 1 therm = 10⁵ Btu; 1 quad = 10¹⁵ Btu ≈ 1 EJ; 1 ton of refrigeration = 12,000 Btu/hr absorbed.

^b The calorie represents the heat that raises 1 g of water 1°C. The above is the International Table calorie, or IT calorie. A “thermochemical” calorie of 4.184 J has also been common. The dietitian’s “Calorie” is actually 1 kilocalorie.