As teachers we can choose between

(a) sentencing students to thoughtless mechanical operations and
(b) facilitating their ability to think.

If students' readiness for more involved thought processes is bypassed in favor of jamming more facts and figures into their heads, they will stagnate at the lower levels of thinking. But if students are encouraged to try a variety of thought processes in classes, then they can … develop considerable mental power. Writing is one of the most effective ways to develop thinking.

—Syrene Forsman

Reference: Forsman, S. (1985). "Writing to Learn Means Learning to Think." In A. R. Gere (Ed.), *Roots in the sawdust: Writing to learn across the disciplines* (pp. 162-174). Urbana, IL: National Council of Teachers of English.

Professor Faith A. Morrison
Department of Chemical Engineering
Michigan Technological University

1

Transport/Unit Operations

Professor Faith A. Morrison
Department of Chemical Engineering
Michigan Technological University

CM2120—Fundamentals of ChemE 2 (Steady Unit Operations Introduction)
CM3110—Transport/Unit Ops 1 (Momentum & Steady Heat Transport, Unit Operations)
CM3120—Transport/Unit Ops 2 (Unsteady Heat Transport, Mass Transport, Unit Operations

www.chem.mtu.edu/~fmorriso/cm3210/cm3210.html

2

CM3120 Transport/Unit Operations 2

Professor Faith A. Morrison
Department of Chemical Engineering
Michigan Technological University

Primary Text:
Christie J. Geankoplis, Transport Processes and Unit Operations, 4th Edition, Prentice Hall, New York (2003).

*Free electronically!

www.chem.mtu.edu/~fmorriso/cm3120/cm3120.html

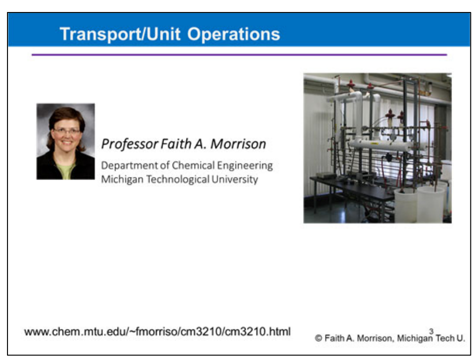
3

Michigan Tech

We seek to be

Thinking Engineers

Reflective
Insightful
Courageous
Confident



4

Why study transport/unit ops?

Michigan Tech

Image: wikipedia.org

Image: planetforward.ca

5

Why study transport/unit ops?

Michigan Tech

- Modern engineering systems are **complex** and often cannot be operated and maintained without analytical understanding

Image: wikipedia.org

Image: planetforward.ca

6

Why study transport/unit ops?

Michigan Tech

- Modern engineering systems are **complex** and often cannot be operated and maintained without analytical understanding
- Design of **new** systems will come from high-tech innovation, which can only come from detailed, analytical understanding of how physics/nature works

Image: wikipedia.org

Image: planetforward.ca

7

Why study transport/unit ops?

Michigan Tech

- Modern engineering systems are **complex** and often cannot be operated and maintained without analytical understanding
- Design of **new** systems will come from high-tech innovation, which can only come from detailed, analytical understanding of how physics/nature works
- **Real** systems are characterized through experimentally determined data correlations (obtained through dimensional analysis)

Image: wikipedia.org

Image: planetforward.ca

8

Where are we now?

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9

Where are we now?

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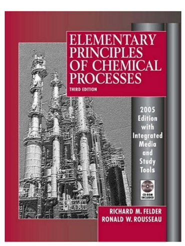
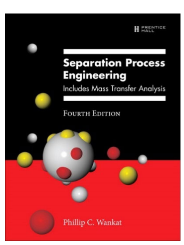
CM2110



Summary

CM2110/CM3215
1. Steady mass balances
2. Steady energy balances (how to calc. energy)
3. MEB-Mechanical Energy Balance
4. Phase equilibria (Raoult's Law)

CM2120



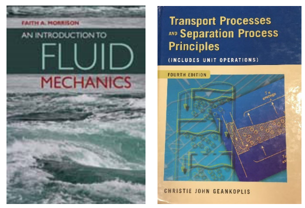
CM2120/CM3215
1. MEB-Mechanical Energy Balance (with friction)
2. Pumps
3. Heat exchangers
4. Introduction to Unit Operations
5. *Staged* Unit Operations (distillation, absorption)

10

Where are we now?

Michigan Tech

CM3110

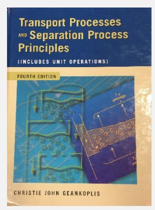


Summary

CM3110

1. Steady *momentum* balances (macro and micro)
2. *Rate-based* heat transfer processes (Fourier's law, heat transfer coefficients, radiation)
3. Data correlations for $f(\text{Re})$, $\text{Nu}(\text{Re}, \text{Pr}, \frac{L}{D})$
4. Unit Operations involving heat transfer (Heat Exchangers)

CM3120



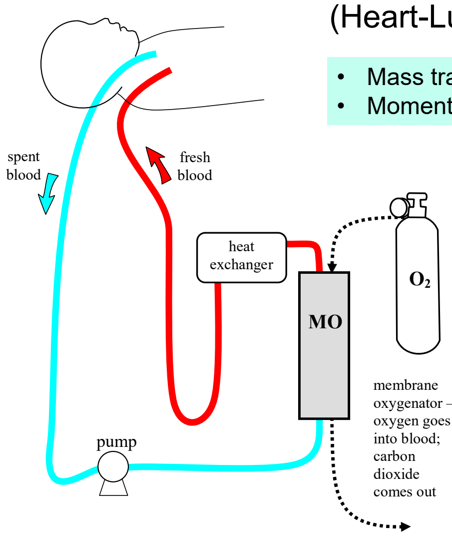
CM3120

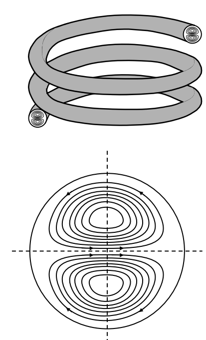
1. Unsteady energy balances
2. *Rate-based* mass-transfer processes (Fick's law, mass transfer coefficients)
3. Data correlations for $\text{Nu}_{AB}(\text{Re}, \text{Sc}, \frac{L}{D})$
4. Unit Operations involving mass transfer (separators)

11

Membrane Oxygenator, MO
(Heart-Lung Machine)

- Mass transfer
- Momentum transfer





Secondary flow drives the O_2 mass transfer

12

Where are we going?

Michigan Tech

+CM3510—Chemical Reaction Engineering

- Performance of chemical reactors
- Advanced chemical kinetics

+CM3230—Thermodynamics for Chemical Engineers

- Non-ideal solutions
- Mixtures
- More complex chemical behavior

CM4110/20—Unit Operations/Chemical Plant Operations Lab

- Capstone, hands-on study of the operation of units that produce chemical transformations

CM4855/4860/1—Chemical Engineering Process Analysis & Design

- Capstone, applied engineering of processes that produce chemical transformations

CM4310—Safety/Environment

13

What's the plan?

Michigan Tech

14

CM3120 Transport/Unit Ops 2

Michigan Tech

Class 1 Outline

1. Class webpage: https://pages.mtu.edu/~fmorriso/cm3120/cm3120.html
2. Review *Course Policies* (7 page handout)
3. *Syllabus* (schedule of MW topics, exams, Fridays)
4. *Study Guide Project, Friday UO Worksheets*
5. *Study Guide for Module 1*
6. Exam 1: Wednesday 20 January 2021 (week from Wednesday)
7. Honor code
8. Questions?
9. Get started

15

All materials are on the course web page:

pages.mtu.edu/~fmorriso/cm3120/cm3120.html

Some links are in Canvas, but most of our materials are on the website.

Course Structure Materials	
Course Policies	Rules, grading policies, advice for doing well (The Checklist Manifesto)
Course Syllabus	
Announcements	Exam 1 (week 2): Wednesday January 20, 2021 Exam 2 (week 8): Wednesday, March 3, 2021 Exam 3 (week 11): Wednesday, March 31, 2021 Final exam (week 15): As scheduled by the registrar.
Student Office Hours	on Zoom or by appointment
Resources	
Lecture Slides	Hand notes
Study Guides Planning Calendars Hand notes from class sessions	
Readings	
Assignments	
Study Guide Project	
Homeworks, Prior Exams	
Friday Unit Operations Project	
Additional Resources	
DrMorrisonMTU	<------Check out Dr. Morrison's YouTube channel (or make a request)
Advice on how to study	
Miscelaneous	
Movies on Transport	
Supplementary Handouts	<------There are some great resources here! There are links to many of the handouts.
Frequently Asked Questions (FAQ's	
Links to Other Information	

16

CM3120 Learning Plan

Michigan Tech

I have:

1. Chosen topics—four modules
2. Suggested readings
3. Will provide lectures
4. Assigned problems (4 homeworks)
5. Produced **Study Guides** (4 modules)
6. Scheduled class sessions for problem solving
7. Schedule class sessions for UO project (4 Fridays)
8. Structured a grading system
   - Four exams
   - Study Guide Project
   - Unit Operations Worksheets

17

Modules

Module 1: Intro and prerequisite material
Module 2: Unsteady state heat transfer
Module 3: Diffusion & mass transfer I
Module 4: Diffusion & mass transfer II

18

Lectures

CM3120 Transport/UO II, spring 2021

Week	lecture	w/in Module	Module	Date	
1	1		1	Monday, January 11, 2021	Course introduction
1	2		1	Wednesday, January 13, 2021	Prerequisite review-steady heat xfer and dim analysis
2				~~Monday, January 18, 2021~~	Class Cancelled, Martin Luther King Jr. Day
2				Wednesday, January 20, 2021	**EXAM 1**
3	3	I	2	Monday, January 25, 2021	(Lec I) Intro to unsteady state heat transfer
3	4	II	2	Wednesday, January 27, 2021	(Lec II) Unsteady micro-E-balance (Will pipes freeze?)
4	5	III,	2	Monday, February 1, 2021	(LecIII) Unsteady macro-E-Balance
4	6	IV,V	2	Wednesday, February 3, 2021	(LecIV) Dimensonal Analysis (LecV) Low Biot number: lumped parameter method
5	7	VI	2	Monday, February 8, 2021	(LecVI) Short Cut Solutions-Heissler, Gurney Lurie charts Butter problem
5	8	VII	2	Wednesday, February 10, 2021	(LecVII) Full analytical solutions
6	9	I	3	Monday, February 15, 2021	(LecI) Introduction to diffusion/mass transfer
6			3	~~Wednesday, February 17, 2021~~	Class Cancelled Career Fair
7	10	II	3	Monday, February 22, 2021	(LecII) Quick Start 1: 1D radial evaporation
7	11	III	3	Wednesday, February 24, 2021	(LecIII) Quick Start 2: Film model for mass transfer
8	12	IV	3	Monday, March 1, 2021	(LecIV) Cycle back: Development of Fick's law
8				Wednesday, March 3, 2021	**EXAM 2**
				Monday, March 8, 2021	Spring Break
				Wednesday, March 10, 2021	Spring Break
9	13	V	3	Monday, March 15, 2021	(LecV) Microscopic species A mass balance
9	14	VI	3	Wednesday, March 17, 2021	(LecVI) Heterogeneous catalysis in a reactor
10	15	I	4	Monday, March 22, 2021	(Lec I) Mass transfer in distillation and absorption
10	16	II	4	Wednesday, March 24, 2021	(Lec II) Linear driving force model (mass xfer coeff)
11	17		4	Monday, March 29, 2021	(Lec II continues)
11				Wednesday, March 31, 2021	**EXAM 3**
12	18	III	4	Monday, April 5, 2021	(LecIII) Species A mass balances-linear driving force model
12	19		4	Wednesday, April 7, 2021	(LecIII continues)
13	20	IV	4	Monday, April 12, 2021	(LecIV) Dimensional analysis in species A mass transfer
13	21		4	Wednesday, April 14, 2021	(LecIV continues)
14	22	V	4	Monday, April 19, 2021	(LecV) Overall mass transfer coefficient
14				Wednesday, April 21, 2021	Exam review
15					**FINAL EXAM**

19

Fridays

Week	module	date	Friday Schedule	Deliverable	Exams
1	1	Friday, January 15, 2021	Problem session Module 1		
2	2	Friday, January 22, 2021	Problem session Module 2	Mod 1 SG	Exam 1
3	2	Friday, January 29, 2021	Distillation (conventional, azeotropic, multicomponent)		
4	2	~~Friday, February 5, 2021~~	Winter Carnival		
5	2	Friday, February 12, 2021	Propblem session Module 2	UO 1 W	
6	3	Friday, February 19, 2021	Gas absorption-packed column and tray towers		
7	3	Friday, February 26, 2021	Problem session Module 3	UO 2 W	
8	3	Friday, March 5, 2021	Problem session Module 3	Mod 2 SG	Exam 2
	3	~~Friday, March 12, 2021~~	Spring Break		
9	3	Friday, March 19, 2021	Membrane Separation (RO, micro/ultra filtration)		
10	3	Friday, March 26, 2021	Problem session Module 3	UO 3 W	
11	4	Friday, April 2, 2021	Problem session Module 4	Mod 3 SG	Exam 3
12	4	Friday, April 9, 2021	Liquid-Liquid Extraction		
13	4	Friday, April 16, 2021	Problem session Module 4	UO 4 W	
14	4	Friday, April 23, 2021	Problem session Module 4	Mod 4 SG	
					Final

20

Study Guide Project

Puts you in charge of your learning

Study Guides answer questions you have about your learning.

You decide what learning activities work best for you.

What is the point of this class?

What am I supposed to be learning?

What skills will I have by the end of the course?

What should I be focusing on to do well in the course?

Study Guide for CM3120 Transport II
Module 1 Prereq Material Unsteady Heat/Mass Xfer

To do well on the test, you should be able to do the following:

Material and system properties for heat transfer

1. Compare and contrast *thermal conductivity* and *heat capacity*
2. Define *heat transfer coefficient* and describe the engineering scenario in which heat transfer coefficient is a useful tool …

21

Study Guide Project

Morrison Transport/Unit Ops 2

Study Guide for CM3120 Transport II
Module 1 Prereq Material Unsteady Heat/Mass Xfer
Morrison Spring 2021

The test will cover material and system properties for heat transfer, macroscopic energy balances, heat calculations on liquids and gases, microscopic energy balances, transport laws, calculating engineering quantities of interest, dimensional analysis, calculations with data correlations, and the supporting mathematics.

To do well on the test, you should be able to do the following:

Material and system properties for heat transfer

1. Compare and contrast *thermal conductivity* and *heat capacity*
2. Define *heat transfer coefficient* and describe the engineering scenario in which heat transfer coefficient is a useful tool
3. Compare and contrast *thermal conductivity* k, *heat transfer coefficient* h, and *overall heat transfer coefficient* U
4. Distinguish between a *material* property or a *system* property in a momentum or heat transfer scenario
5. Compare and contrast *conduction*, *natural* and *forced convection*, and *radiation* heat transfer

Macroscopic open system mass and energy balances (reference, Felder and Rouseau)

6. Explain the individual terms of the macroscopic open system energy balance
7. Compare and contrast the macroscopic open system energy balance with the mechanical energy balance (MEB)
8. Perform and solve macroscopic open system mass and energy balances on elementary systems such as mixers, heat exchangers, separators, and distillation columns
9. Perform and solve MEB calculations for frictional losses, shaft work, pressure, or related quantities for systems including valves, fittings, turbines, and pumps

Heat calculations (liquids, gases, and saturated vapors)

10. Define the *dew point* and explain how to measure it
11. Define the *bubble point* and explain how to measure it; explain what systems it applies to
12. Compare and contrast *saturation* and *equilibrium*
13. Define *enthalpy* and describe its significance for calculating heat flow $\dot{Q}$ for flowing liquids and gasses
14. Calculate the heat required to raise the temperature of a gas or liquid stream by a certain amount (mass/molar flow rate or volumetric flow rate given)
15. Calculate the heat released when a certain amount of saturated vapor (for example, saturated steam) condenses, mass/molar rate of condensation given

Microscopic energy balances, transport laws, and engineering quantities of interest

16. Describe the transport laws for momentum and energy transport (give formulas and meaning of variables they include)
17. Simplify the microscopic energy balance for elementary scenarios (steady); arrive at a differential equation to solve for the temperature field
18. Identify and apply temperature boundary conditions for heat transfer scenarios

27-Dec-20 1

Morrison Transport/Unit Ops 2

19. Identify and apply Newton's law of cooling boundary conditions (linear driving force heat transfer model) for heat transfer scenarios
20. Calculate temperature fields for elementary scenarios (steady)
21. Calculate engineering quantities of interest (flow rate Q, fluid force on a surface $\underline{\mathcal{F}}$, (stretch) fluid torque $\underline{\mathcal{T}}$) given pressure and stress fields

Dimensional Analysis in fluid mechanics and heat transfer (steady)

22. Explain the purpose of dimensional analysis
23. List dimensionless numbers that appear in the nondimensionalized microscopic mass balance (give formula and meaning, e.g. for which material)
24. List dimensionless numbers that appear in the nondimensionalized microscopic momentum balance for pipe flow (give formula and meaning, e.g. for which material)
25. List dimensionless numbers that appear in the nondimensionalized microscopic energy balance for forced convection (give formula and meaning, e.g. for which material)
26. (stretch) Contrast the momentum nondimensionalization for pipe flow and for flow around a sphere
27. List dimensionless numbers that result from nondimensionalizing engineering quantities of interest (flow rate Q, fluid force on a surface $\underline{\mathcal{F}}$, (stretch) fluid torque $\underline{\mathcal{T}}$)
28. Explain the meaning of *data correlation*; explain where we obtain data correlations
29. Provide an example of a data correlation used in fluid mechanics
30. Provide an example of a data correlation used in steady heat transfer

Complex flow scenarios. From material properties and geometry:

31. Predict pressure drop in turbulent pipe flow from flow rate
32. Predict volumetric flow rate Q in turbulent pipe flow from pressure drop
33. Predict pressure drop or flow rate Q for flow through packed beds
34. Predict heat loss $\dot{Q}$ in engineering scenarios involving forced convection, natural convection, and radiation

Mathematics through differential equations

35. Calculate two- and three-dimensional integrals of functions of up to three variables
36. Calculate partial derivatives of functions of more than one variable
37. Sketch a vector or vector field in a coordinate system
38. Identify limits of integration for quantities (for example, mass, volume, area) to be evaluated by 2D and 3D integrations in rectangular, cylindrical, and spherical coordinates
39. Calculate double (surface) and triple (volume) integrals with constant limits of integration in rectangular, cylindrical, and spherical coordinates

References:

- Richard Felder and Ronald Rouseau, *Elementary Principles of Chemical Processes*, 2nd Edition 1986
- Faith A. Morrison, *An Introduction to Fluid Mechanics*, 2013, Cambridge, NY
- Christie J. Geankoplis, *Transport Processes and Unit Operations*, 4th Edition, Prentice Hall, New York (2003)

27-Dec-20 2

22

Fridays

Four worksheets (one for each of 4 UOs) combine to be the 5th Study Guide submission

CM3120 Transport UO 2, Morrison 2021

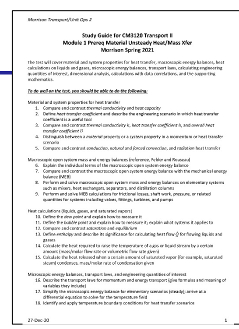
Name:

Name of Unit Operation: ____________________

1. Describe the unit operation
2. Provide the basics of mass and energy streams in the unit (provide a flowsheet that shows mass and energy flows)
3. Provide design and operating principles; what is the role of transport in this unit's operation?
4. Provide most common/less-common uses of this particular unit operation
   Most common use:
   Less common uses:
5. Three important limitations to this UO
   a.
   b.
   c.
6. Up to three chemical engineering production schemes that currently employ the unit (and how they employ it)
   a.
   b.
   c.
7. Indicate how this unit operation differs from other units/processes sometimes used for the same purpose
8. Indicate the references you used for this submission:

23

It is up to you how to proceed.



Plausible course of action:

i. Start with the **Study Guide** for the module.
ii. Look for problems (from those assigned or in one of the texts) that would demonstrate that you have the skill/knowledge listed on the Study Guide.
iii. Do those problems; refer to readings & lectures to learn how to solve. Save copies of your work to submit as part of the Study Guide project.
iv. Bring questions to the class sessions; we will do problems both all together (me leading).
v. Form a study group with classmates; I can help introduce you to interested team mates
vi. Bring questions to student office hours.
vii. Work to refine your transport skills/knowledge.
viii. Show your mastery on the exams; stretch yourself if you seek top performance.

24

Handy Sheet for Unit Conversions

Michigan Tech

Prof. Faith A. Morrison
Department of Chemical Engineering
MichiganTech

FACTORS FOR UNIT CONVERSIONS

Quantity	Equivalent Values
Mass	1 kg = 1000 g = 0.001 metric ton = 2.20462 lb_m = 35.27392 oz 1 lb_m = 16 oz = 5 x 10^{-4} ton = 453.593 g = 0.453593 kg
Length	1 m = 100 cm = 1000 mm = 10^6 microns (μm) = 10^{10} angstroms (Å) = 39.3701 in = 3.28084 ft = 1.09361 yd = 0.000621371 mile 1 ft = 12 in. = 1/3 yd = 0.3048 m = 30.48 cm
Volume	1 m^3 = 1000 liters = 10^6 cm^3 = 10^6 ml = 35.31467 ft^3 = 219.969 imperial gallons = 264.172 gal = 1056.69 qt 1 ft^3 = 1728 in^3 = 7.48052 gal = 0.028317 m^3 = 28.3168 liters = 28,316.8 cm^3
Force	1 N = 1 kg·m/s^2 = 10^5 dynes = 10^5 g·cm/s^2 = 0.22481 lb_f 1 lb_f = 32.174 lb_m·ft/s^2 = 4.4482 N = 4.4482 x 10^5 dynes
Pressure	1 atm = 1.01325 x 10^5 N/m^2 (Pa) = 101.325 kPa = 1.01325 bars = 1.01325 x 10^6 dynes/cm^2 = 760 mm Hg at 0° C (torr) = 10.333 m H_2O at 4° C = 14.696 lb_f/in^2 (psi) = 33.9 ft H_2O at 4°C 100 kPa = 1 bar
Energy	1 J = 1 N·m = 10^7 ergs = 10^7 dyne·cm = 2.778 x 10^{-7} kW·h = 0.23901 cal = 0.7376 ft·lb_f = 9.47817 x 10^{-4} Btu
Power	1 W = 1 J/s = 0.23885 cal/s = 0.7376 ft·lb_f/s = 9.47817 x 10^{-4} Btu/s = 3.4121 Btu/h = 1.341 x 10^{-3} hp (horsepower)
Viscosity	1 Pa·s = 1 N·s/m^2 = 1 kg/m·s = 10 poise = 10 dynes·s/cm^2 = 10 g/cm·s = 10^3 cp (centipoise) = 0.67197 lb_m/ft·s = 2419.088 lb_m/ft·h
Density	1 kg/m^3 = 10^{-3} g/cm^3 = 0.06243 lb_m/ft^3 10^3 kg/m^3 = 1 g/cm^3 = 62.428 lb_m/ft^3
Volumetric Flow	1 m^3/s= 35.31467 ft^3/s=15,850.32 gal/min (gpm) 1 gpm = 6.30902 x 10^{-5} m^3/s=2.228009 x 10^{-3} ft^3/s=3.7854 liter/min 1 liter/min=0.26417 gpm

Ver. 30-Oct-2014

Temperature	$T(^\circ C) = \frac{5}{9}\left[T(^\circ F) - 32\right]$ $T(^\circ F) = \frac{9}{5}T(^\circ C) + 32 = 1.8T(^\circ C) + 32$
Absolute Temperature	T(K) = T(°C) + 273.15 T(°R) = T(°F) + 459.67
Temperature Interval (ΔT)	1 C° = 1 K = 1.8 F° = 1.8 R° 1F° = 1 R° = (5/9) C° = (5/9) K

USEFUL QUANTITIES

SG = $\rho(20^\circ C)/\rho_{water}(4^\circ C)$

$\rho_{water}(4^\circ C)$ = 1000 kg/m^3 = 62.43 lb_m/ft^3 = 1.000 g/cm^3
$\rho_{water}(25^\circ C)$ = 997.08 kg/m^3 = 62.25 lb_m/ft^3 = 0.99709 g/cm^3

g = 9.8066 m/s^2 = 980.66 cm/s^2 = 32.174 ft/s^2

$\mu_{water}(25^\circ C)$ = 8.937 x 10^{-4} Pa·s = 8.937 x 10^{-4} kg/m·s
= 0.8937 cp =0.8937 x 10^{-2} g/cm·s = 6.005 x 10^{-4} lb_m/ft·s

Composition of air:

N_2	78.03%
O_2	20.99%
Ar	0.94%
CO_2	0.03%
H_2, He, Ne, Kr, Xe	0.01%
	100.00%

M_{air} = 29 g/mol = 29 kg/kmol = 29 lb_m/lbmole

$\hat{C}_{p,water}(25^\circ C)$ = 4.182 kJ/kg K = 0.9989 cal/g°C = 0.9997 Btu/lb_m°F

R = 8.314 m^3·Pa/mol·K = 0.08314 liter·bar/mol·K = 0.08206 liter·atm/mol·K
= 62.36 liter·mm Hg/mol·K = 0.7302 ft^3·atm/lbmole·°R
= 10.73 ft^3·psia/lbmole·°R
= 8.314 J/mol·K
= 1.987 cal/mol·K = 1.987 Btu/lbmole·°R

Ver. 30-Oct-2014

pages.mtu.edu/~fmorriso/cm310/convert.pdf

25

CM3120: Module 1

Introduction and Prereq Material

I. Introduction
II. Review of Prerequisite Material
   a. Microscopic energy balances
   b. Fourier's law of heat conduction (k, homogeneous)
   c. Newton's law of cooling (h, at a boundary)
   d. Resistances due to k and h
   e. Solving for the steady temperature field $T(x,y,z)$
   f. Dimensional analysis in heat transfer for h
   g. h Data correlations for forced and free convection
   h. h For radiation heat transfer

26

Michigan Tech

Prerequisite material

Exam 1: Next Wednesday

7:00-11:59pm; 2 hours, 15 minutes permitted

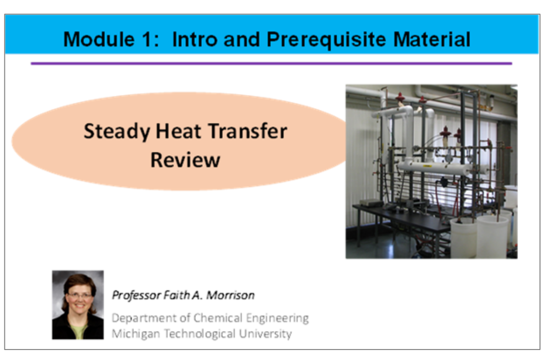
Exam topics: See Study Guide 1

Online Exam System

1. *You are on your honor*
2. Include signed pledge in submitted solution: "*On my honor, I agree to abide by the rules stated in the course materials.*"
3. You may work for up to two hours and 15 minutes (135 min)
4. Closed book, closed notes.
5. Two-page 8.5" by 11" study sheet allowed, double sided; you may use a calculator; no uses of internet
6. Please text clarification questions to Dr. Morrison 906-487-9703.
7. All work submitted for the exam must be your own.

27

NEXT: Steady Heat Transfer Review



28