2013

CHME 223: Chemical Engineering Thermodynamics I—A Peer Review of Teaching Project Benchmark Portfolio

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Course Portfolio Project

University of Nebraska-Lincoln

Department of Chemical and Biomolecular Engineering

Course: Chemical Engineering Thermodynamics I

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Spring 2013

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I. Course Portfolio Objectives

The Department of Chemical and Biomolecular Engineering has started a systematic student self-assessment process for all required undergraduate courses last year. This is to better align the department with the ABET's accreditation process requirements. My main purpose in participating in the Peer Review of Teaching Project is to gain different perspective for the evaluation process. I am also interested to reexamine my syllabus and course objectives for their alignment with the evaluation process

This portfolio is intended to provide a broad overview of the course. Initially, when I decided to write this portfolio my intension was for it to help me in the student's outcome assessment of teaching for the course and in a broader scope for my department's effort in establishing a systematic student's outcome assessment process. However, as I became more familiar with the program I realized that other aspects of the course could also benefit from this portfolio. My goal for this portfolio is to be broad with emphasis on course objectives, delivery methods and their assessment. I would also like for this portfolio to help me identify if the material covered in the course are, firstly adequate to establish the course objectives and furthermore if they are adequate for students to develop masterly of the concepts.

II. Description of Course and Students

This course is the first of two courses in thermodynamics as applied to problems in chemical engineering. It covers the properties of single-component systems and certain processes involving them. The second course introduces multi-component systems. The theoretical bases of classical thermodynamics including the 1st and 2nd laws and their applications are studied in some detail. Some emphasis is placed on the derivation of certain partial derivatives from which, using an equation of state and heat capacity data, the thermodynamic properties of pure substances can be obtained. Equations of state themselves are also studied in some detail.

The course is open to the students in the College of Engineering, however, almost all students in this class are Chemical and Biomolecular Engineering majors. The course is required for completion of an undergraduate degree in Chemical and Biomolecular Engineering. The course is offered once a year and has about 30-45 students enrolled in it. The course is offered to the second semester sophomores and most of the students enrolled in the class are sophomores. This course like most of the required core courses for the chemical engineering discipline is in a sequence of courses. It has a chemical engineering course as its prerequisite (Chemical Engineering Mass and Energy Balances with a grade of C- or better). The course also has Introduction to Computer Science (CSCE 150N) as a prerequisite or parallel. This course is a prerequisite for the second course in thermodynamics and for the Equilibrium Stage Operations course. The two courses in in thermodynamics along with two courses in transport operations, a course in equilibrium state operations and a course in reaction kinetics lay the foundation for the chemical engineering capstone courses in design and unit operations laboratory.

III. Course Goals and Objectives

A. Course goals

To learn the basic principles and applications of thermodynamics to the analysis of problems arising in chemical and other related engineering disciplines. Specific goals are:

1. To introduce students to thermodynamics from a chemical engineering viewpoint.
2. To introduce students to the scope and domain of thermodynamics and an understanding of the 1st law and 2nd law of thermodynamics.
3. To provide students the knowledge of P-V-T relationship and thermodynamic properties.
4. To provide students the knowledge to calculate work, heat, and changes in the energy of a system in a process.
5. To provide students the knowledge to analyze power and refrigeration cycles.
6. To introduce students to the concept of vapor/liquid equilibrium.
7. To enhance the students' ability to analyze information and solve problems on a complex and thought-based level.

B. ABET Student Outcomes

ABET, the Accreditation Board for Engineering and Technology has established certain criteria for accredited engineering program to be demonstrated by the students completing these programs. These criteria are expected to be met by completing one or more core courses in a given program. The ABET criteria to be met in this class are as follows.

a. An ability to apply knowledge of mathematics, science and engineering.

c. An ability to identify, formulate and solve engineering problems.

k. An ability to use the techniques skills and modern engineering tools necessary for engineering practice.

C. Expected Course Outcomes

At the end of this course the student are expected to:

1. Understand the scope and domain of thermodynamics.

2. Apply the laws of thermodynamics to chemical engineering processes.

3. Identify and use equations of state to describe real fluids.
4. Identify and use the properties of mechanical, thermal and chemical equilibrium to solve scientific and engineering problems.
5. Derive a relationship between any thermodynamic quantity and a small set of measurable thermodynamic quantities using a set of systematic thermodynamic manipulations.
6. Calculate differences in thermodynamic properties using equations of state, charts and tables, and computer resources.
7. Analyze and design power cycles and refrigeration cycles.

IV. Instructional Techniques/Course Material/Course Activities

A. Instructional Techniques and Activities

The course materials are mainly presented in the form of lectures. A combination of the white board and the overhead projectors are used in the presentation of lectures. Lecture material consists of the fundamentals of thermodynamic principles and problems associated with these principles. Lectures are presented along with continuous flow of questions along with the lecture material. There are several reasons for this format. These questions are presented to keep the students engaged, let me gauge the degree of their involvement and understanding of the material and to encourage them to think and to be critical of the presented material. Another method which is used to keep students involved during the class time is the assignment of in class problem where a specific problem which is closely related to the lecture material is introduced and the students are asked to work the problem in class. This is then followed by asking the students to present their work to others which created a way for them to see different approaches to a given situation.

B. Course Material

A textbook and a reference handbook were assigned.

Textbook: Smith, J.M., Van Ness, H.C., Abbott, M.M., "Introduction to Chemical Engineering Thermodynamics", 7th ed. by, McGraw-Hill (2005).

Reference: Perry and Green, *Perry's Chemical Engineering Handbook,* 7th edition, McGraw-Hill Book Company, New York, 1997

V. The Course and the Broader Curriculum

The science of thermodynamics was born to describe the operation of steam engines and their limitations. The name itself denotes power generation from heat but the thermodynamic principals which are experimentally realized to apply to engines, were readily generalized as the laws of thermodynamics. In a broader scope, thermodynamics concerns the transformation of energy from one form to another and the interaction of energy with matter. Thermodynamics applies to a variety of topics in science and engineering and its calculations are essential to many fields including chemical engineering.

The thermodynamics course which is the topic of this portfolio is offered as a core course in the department of chemical engineering. The first chemical engineering thermodynamics is offered to the second semester sophomore students and is followed by the second course which is offered to the first semester junior students. The course is open to the students in the College of Engineering; however, almost all students in the thermodynamic classes are Chemical and Biomolecular Engineering majors. The course is the first of two courses in thermodynamics as applied to problems in chemical engineering. The chemical engineering curriculum emphasizes basic knowledge and applications of transport processes, thermodynamics and kinetics of processes, automatic control, and design, as well as fundamental sciences, mathematics and engineering sciences. Equipment design is emphasized in courses such as fluid mechanics, heat and mass-transfer operations, thermodynamics, and chemical reactor engineering. The two thermodynamics courses are one of the foundations to equipment design.

Thermodynamics is also a topic of interest in mechanical engineering disciplines. While with a different emphasis, thermodynamics is considered as one the most essential subjects in mechanical engineering. Other departments such as chemistry and physics offer thermodynamics, although not by its title but as topics which are incorporated into other titles, example of which are the physical chemistry courses offered in the department of chemistry which extensively covers topics in thermodynamics.

VI. Analysis of Student Learning

A. ***Instructor's assessment***

Examinations: The students took 3 exams with a weight of 15% each. The exams were open book, however, notes were not allowed and were given outside of the class time from 6:00 to 8:00 pm in a pre-specified lecture hall. The examinations were designed to evaluate the student's understanding of the fundamental concepts. Nevertheless, students ability to solve abstract problems were implicitly incorporated in these examinations. The problems on exams, although not in content, but in style were very similar to the problem on the homework assignments and often were picked from the set of problems at the end of the chapters in the textbook. The students also took a final exam with a weight of 30%. All examinations were graded by the instructor and were returned to the students within a week from the time of the exams. Exams 1-3 and the final exam and the solution to the exams are presented in the appendix.

Quizzes: The students took quizzes every Thursday during the course of the semester. The students took ten quizzes with a weight 15% of the their total grade. The focus of the quiz problems were on the material which were discussed in recent lectures and the students were working on their homework assignments. The quizzes were intended to keep students up-to-date with the class discussions. Having quizzes on regular bases also helped with the attendance. The quizzes are presented in the appendix .

Homework assignments: Problems were assigned on weekly bases and were collected at the beginning of the class on the day they were designated as due. The homework problems were viewed as an extremely important part of the course and the students were expected to treat it as such. Also, the students were reminded about the quality of their work on homework problems and the impression that it could make on me and potentially on their future employer. Some of the homework problems were expected to be solved with Mathcad software. The students completed 14 sets of problems during the course of the semester with a weight of 10% of their total grade. The homework assignments were graded by the class teaching assistant. A representative selection of homework assignments is presented in the appendix.

B. Students Self-Assessments and Proposed Continuous Improvement Action

Methodology

Students were asked to make a self-assessment of their understanding of the course material. Two sets of questions were presented to the students. The first set of questions encompassed the course objectives, whereas, the second set of questions covered the ABET a-k criteria which related to the general program outcomes. Students were asked to evaluate their degree of understanding as poor, adequate, well, or extremely well. Students were surveyed three times during the course of the semester right after the first, second and the third exams (03/07/13, 04/02/13 and 04/23/13). In earlier surveys when the material which related to the survey question was not covered at the time of the survey, the answer to some survey questions were specified as: N/A: does not apply. The survey form is presented in Table 1.

Survey Results and Analysis

The first focus of the analysis in this evaluation cycle was to assess potential improvements in weaknesses which were previously identified by the students in achieving the course objectives and the corresponding ABET a-k criteria in the fall 2012 assessment cycle. Another focus of the analysis was to identify potential weaknesses identified by the students in achieving the course objectives and the corresponding ABET a-k criteria in the spring 2013 assessment cycle.

Table 1: Course Self Assessment Form

CHME223 Chemical Engineering Thermodynamics I	**Section:**	**1**
	Term:	**Spring 2013**
	Professor:	**Noureddini**
	Date:	**4/23/2013**

Please identify and rate to which degree you have met the *Course Objectives* and *ABET Student Outcomes:*

1: poor 2: adequate 3: well 4: extremely well N/A: does not apply

	Level of Achievement %				
Course Objectives	**1**	**2**	**3**	**4**	**N/A**
Understand the scope and domain of thermodynamics.					
Apply the laws of thermodynamics to chemical engineering processes.					
Identify and use equations of state to describe real fluids.					
Identify and use the properties of mechanical, thermal and chemical equilibrium to solve scientific and engineering problems.					
Derive a relationship between any thermodynamic quantity and a small set of measurable thermodynamic quantities using a set of systematic thermodynamic manipulations.					
Calculate differences in thermodynamic properties using equations of state, charts and tables, and computer resources.					
Analyze and design power cycles and refrigeration cycles.					

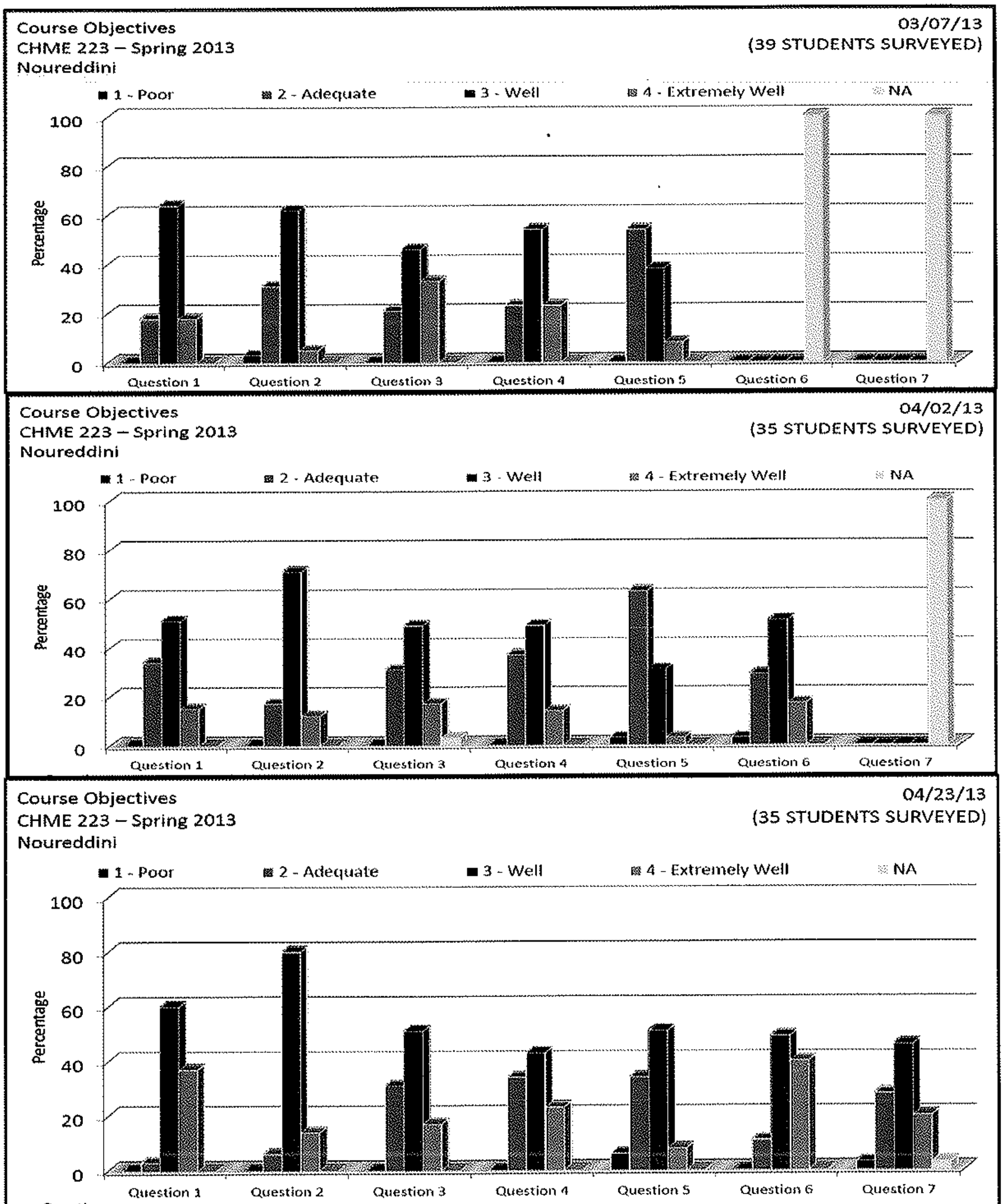
	Level of Achievement %				
ABET Student Outcomes	**1**	**2**	**3**	**4**	**N/A**
(a) an ability to apply knowledge of mathematics, science, and engineering					
(e) an ability to identify, formulate, and solve engineering problems					
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice					

Survey results: The survey results for the course objectives are presented in Figure 1. In general, the results showed a gradual improvement in the students' mastery of the objectives as the semester progresses and toward the end of the semester almost all the students showed adequate or better understanding of the course objectives with more than 2/3 showing well or extremely well understanding of the course objectives. The level of the students' mastery of the course objectives varied for the course objectives with the earlier objectives showing a higher level of achievement by the students compared with the objectives which were covered later during the semester. Objectives 6 and 7 in the first survey and objective 7 in the second survey were not ranked by the students as these topics were not covered at the time these surveys were performed.

Survey analysis: As expected, the level of achievement of the course objectives was increased in time. This trend was more apparent for the objectives which were covered earlier in the semester compared to the ones which were covered later in the semester. In particular, students could benefit from more emphasis on objectives 3, 4, 5, and 7 as about 30% of the students ranked their command of these objectives adequate where our goal for the students was to achieve well or extremely well command of these objectives.

Survey feedback from previous cycle (fall 2012) and potential improvements: Objective 6 was identified in the previous survey for improvement and as was proposed from the previous cycle, a week of class time was added to the coverage of this objective. The survey results at the end of the semester showed a significant improvement in the level of understanding of the students with about 90% of the students surveyed identified their level of command of the objective as well or extremely well. As was proposed in the fall 2012 survey, students completed a third survey toward the end of the semester.

Proposed changes for improvement: The material related to the 4th, 5th and the 6th objectives could benefit from the shortening of the theoretical developments related to these objectives and broadening the application of the fundamental to problem solving. This might be beneficial as due to recent changes in the chemical engineering curriculum, students are now required to take this class as sophomores, whereas, before these changes this class was taken parallel with the physical chemistry class where some overlap of the course material existed.



Questions

1. To introduce students to thermodynamics from a chemical engineering viewpoint.
2. To introduce students to the scope and domain of thermodynamics and an understanding of the 1st law and 2nd law of thermodynamics.
3. To provide students the knowledge of P-V-T relationship and thermodynamic properties.
4. To provide students the knowledge to calculate work, heat and changes in the energy of a system in a process.
5. To calculate differences in thermodynamic properties using equations of state, charts, tables and computer resources.
6. To provide students the knowledge to analyze power and refrigeration cycles.
7. To introduce students to the concept of vapor/liquid equilibrium.

Figure 1: Survey results for the student's self-assessment of the course objectives

ABET a-k criteria

a. An ability to apply knowledge of mathematics, science and engineering.

e. An ability to identify, formulate and solve engineering problems.

k. An ability to use the techniques skills and modern engineering tools necessary for engineering practice.

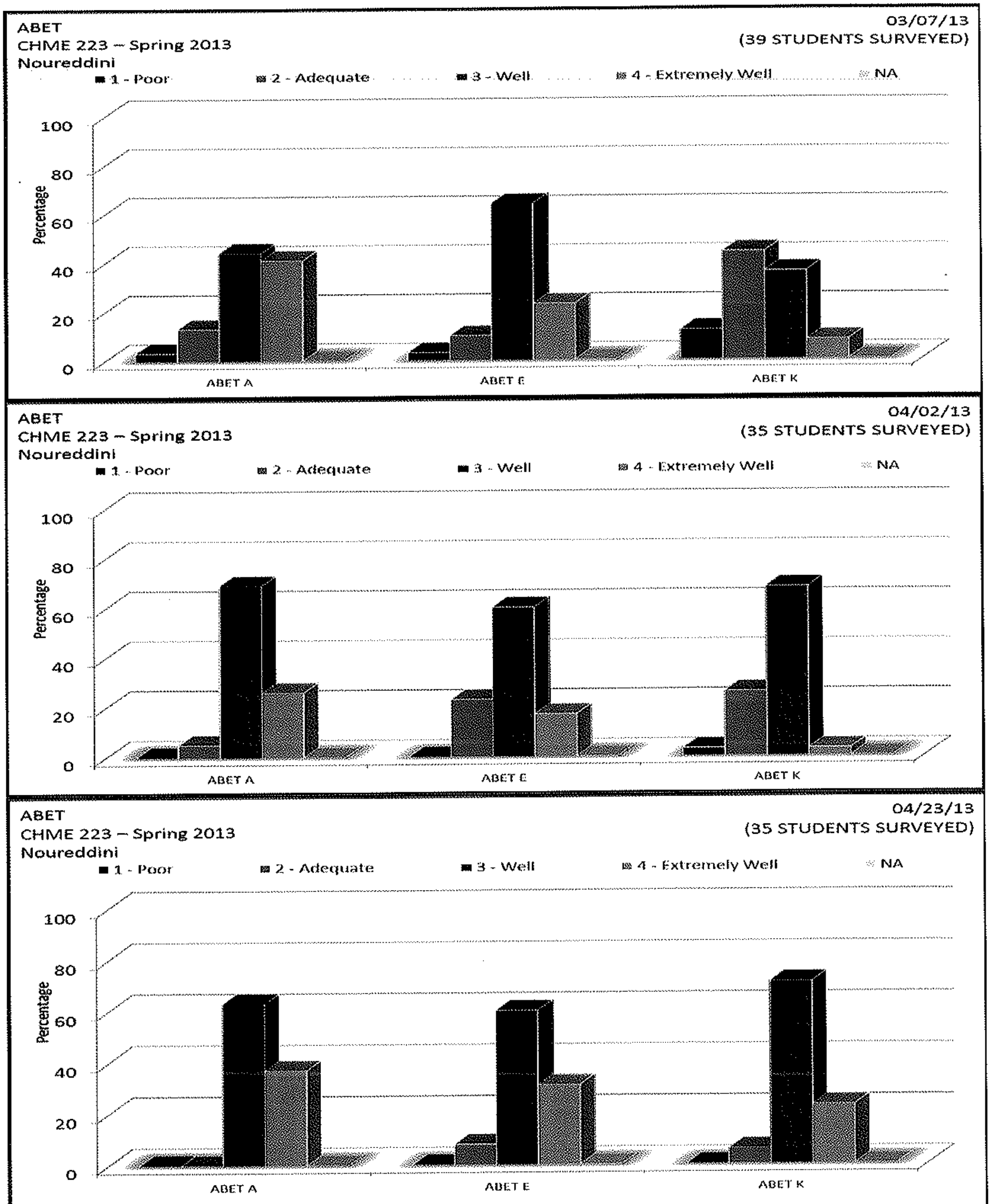
Survey results: The course relates to ABET student outcomes a, e, and k. The survey results for the ABET student outcomes are presented in Figure 2. In all surveyed categories, an overwhelming majority of the respondents (90% or more on the third survey, 04/23/13) rated their level of achievement *as well or extremely well.*

Survey feedback from previous cycle (fall 2012) and potential improvements: Recent changes in the chemical engineering has shifted CHME 223 from the fifth to the forth semester which has resulted, among other things, for the formal introduction of Mathcad to the students in this class. The students are expected to benefit from this in their junior level classes.

Proposed changes for improvement: will continue to have more structured exposure of students to Mathcad in this class. This is expected to be beneficial in the junior level courses that will follow.

C. Analysis of grades and grade trends.

Student's final grades are presented in Figure 3. The overall grade trends were 25% A, 40% B, 30% C, and 5% D and F. The grade trends are expected to correlate with not only the instructor's assessment but also with the student's self-assessments of their understanding of the course material. To examine possible correlation between the grade trends and the student's self-assessment, it was assumed that the student's responses to the survey questions namely: poor, adequate, well and extremely well were reflective as grads of D+F, C, B, and A, respectively. In another word, a student who believes he or she has an extremely well understanding of the course material earned a grade of A, whereas, a student who has a poor understanding of the course material earned a grade of D or F. Examination of Figures 1 and 3 reveals that this correlation was generally observed as on the average 60-70% of the students rated their understanding of the course material as well or extremely well which related well with the 65% of the students who earned As and Bs in the course. Also the 30% of the students who earned Cs for the course correlated well with about 30% of the students (on the average) who ranked their understanding of the course material as adequate.



Questions

A. An ability to apply knowledge of mathematics, science, and engineering.

E. An ability to identify, formulate, and solve engineering problems.

K. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Figure 2: Survey results for the ABET a-k student outcomes.

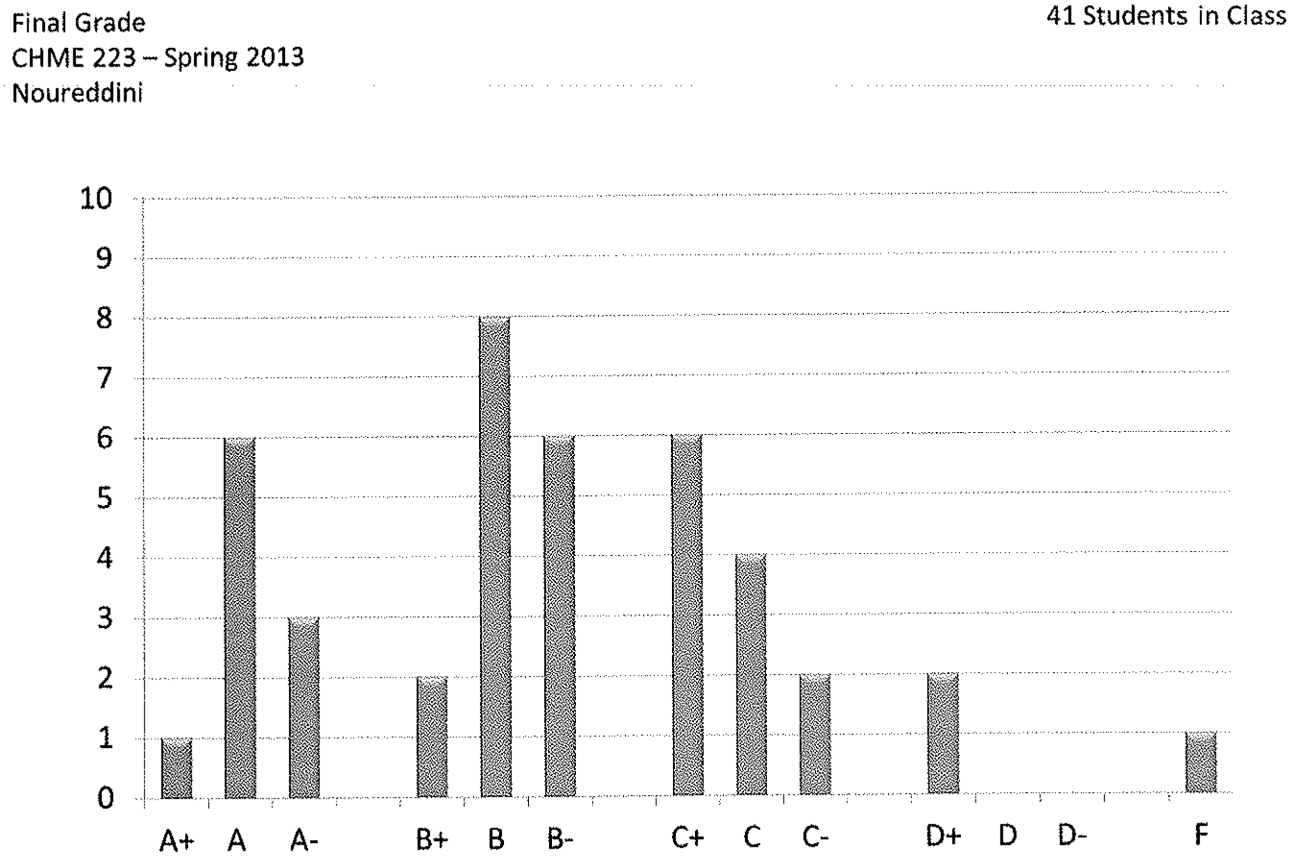


Figure 3: Students final grades.

Appendix

CHME 223 – Chemical Engineering Thermodynamics I
Spring 2013

General Description:

This course is the first of two courses in thermodynamics as applied to problems in chemical engineering. This semester will cover the properties of single-component systems and certain processes involving them. The second semester will introduce multi-component systems. The theoretical bases of classical thermodynamics including the 1st and 2nd laws and their applications are studied in some detail. Some emphasis will be placed on the derivation of certain partial derivatives from which, using an equation of state and heat capacity data, the thermodynamic properties of pure substances can be obtained. Equations of state themselves will also be studied in some detail.

Prerequisites:

A grade of C- or better in Mass and Energy Balance (CHME 202)
Introduction to Computer Science (CSCE 150E) or parallel

Lecture:

9:30 – 10:45 TT
110 Othmer Hall

Instructor:

Hossein Noureddini
Department of Chemical and Biomolecular Engineering
Office: 207H Othmer Hall
Tel: 402-472-2751; Fax: 402-472-6989; Email: hnoureddini@unl.edu
Office hours: Open door policy – available most of the time between 9:00 am and 4:00 pm M-F. You may also make a specific appointment.

Textbook:

Smith, J.M., Van Ness, H.C., Abbott, M.M., "Introduction to Chemical Engineering Thermodynamics", 7th ed. by, McGraw-Hill (2005).

Reference:

Perry and Green, *Perry's Chemical Engineering Handbook,* 7th edition, McGraw-Hill Book Company, New York, 1997

Goals:

1. To introduce students to thermodynamics from a chemical engineering viewpoint.
2. To introduce students to the scope and domain of thermodynamics and an understanding of the 1st law and 2nd law of thermodynamics.
3. To provide students the knowledge of P-V-T relationship and thermodynamic properties.
4. To provide students the knowledge to calculate work, heat, and changes in the energy of a system in a process.
5. To provide students the knowledge to analyze power and refrigeration cycles.

6. To introduce students to the concept of vapor/liquid equilibrium.

At the end of this course the student will be able to:

1. Understand the scope and domain of thermodynamics.
2. Apply the laws of thermodynamics to chemical engineering processes.
3. Identify and use equations of state to describe real fluids.
4. Identify and use the properties of mechanical, thermal and chemical equilibrium to solve scientific and engineering problems.
5. Derive a relationship between any thermodynamic quantity and a small set of measurable thermodynamic quantities using a set of systematic thermodynamic manipulations.
6. Calculate differences in thermodynamic properties using equations of state, charts and tables, and computer resources.
7. Analyze and design power cycles and refrigeration cycles.

Grading:

Homework	10%
Quizzes	15%
Hour Exams (3)	45%
Final Exam	30%
	100%

Unless otherwise stated, there will be a quiz every Thursday during the course of the semester. The final exam will be on Wednesday December 12 from 10:00 to 12:00 noon and will cover the complete course material.

The final grade will be determined as follows:

A+	97.0 to 100%
A	93.0 to 96.9%
A-	90.0 to 92.9%
B+	87.0 to 89.9%
B	83.0 to 86.9%
B-	80.0 to 82.9%
C+	77.0 to 79.9%
C	73.0 to 76.9%
C-	70.0 to 72.9%
D+	67.0 to 69.9%
D	63.0 to 66.9%
D-	60.0 to 62.9%
F	59.9 and under

Makeup examination policy. Illness, with written documentation from the UN-L Health Center, or a University-Authorized family emergency (also in writing) is the only acceptable excuses for missing a scheduled exam. In such a case, the weighting of the exam missed will be dropped from the final average (all others scaled up). Students not having an acceptable excuse (as determined by the instructor) will receive zero credit.

Class participation. Students are expected to participate in class discussions. Students also will be called to discuss pre assigned problems during the class. Students are expected to go over the problem statement and provide solutions or solution paths for the problem. Student names are called from a randomly pre specified list.

Homework policy. The homework problems are an extremely important part of the course and they should be treated as such. Also, how you present your work gives an important impression of the quality of your work, to your future employer and me. Homework problems are expected to be solved with Mathcad software. Problems will be collected at the beginning of the class on the day they were designated as due.

Student collaboration policy. Students are encouraged to discuss homework problems with each other, the instructor, or others. This is good professional practice.

NOTE: All written and programming work must be solely your own effort. Any homework that appears to be duplicates will subject all involved individuals to charges of academic dishonesty. The consequences will include receiving zero credit for that assignment and a grade of "F" on a second incident. Any evidence that a student has access to and/or is copying homework from the Instructor's Manual for the text for this course will result in that student receiving zero for all homework for this course.

Group Assignments. The following general rules must be observed on all group assignments.

1. Students may choose their own groups subject to the instructions in the problem statement.
2. The instructor must be given written notice of group membership within two class periods after the assignment is made.
3. Persons may leave or be ejected from groups, provided that the instructor is given written notice of such changes signed by all group members. No changes in group membership are permitted within 72 hours of the assignment due date.
4. Collaboration should not cross group lines when groups are working on the same problem.

Attendance Policies: Attendance at all classes is strongly recommended. Attendance is required for all examinations. Zero points will be assigned to any quizzes missed. **There will be no make-up for quizzes.** If a student arrives late for any quiz or examination, the student must complete and turn in that examination or quiz at the same scheduled time as all other students.

Withdrawals: The responsibility for withdrawals is completely up to the student.

Incomplete grades: A grade of Incomplete (I) is given **only if the student is passing** and cannot complete the required work for reasons beyond the student's control.

Tentative schedule	Topics to be covered	Reading Assignment
Week 1:	Scope of thermodynamics	Sections 1.1 - 1.9
	Basic definitions	
	First law of thermodynamics	Sections 2.1 - 2.3
Week 2:	Labor Day	
	First law for closed systems	Sections 2.4 - 2.9
	Equilibrium	
	The reversible process	
Week 3:	Enthalpy	Sections 2.10 - 2.12
	Heat capacity	
	First law for open systems	
	P-V-T behavior of gases	Sections 3.1 - 3.2
	Virial equations of state	
Week 4:	Ideal gas law	Sections 3.3 - 3.7
	Cubic equations of state	
	Generalized correlations for gases and liquids	
	1st Hour Exam	
Week 5:	Heat effects	Sections 4.1, 4.2, 4.4
	Sensible heat effects	
	Standard heat of formation	
Week 6:	Standard heat of reaction	Sections 4.3 - 4.7
	Standard heat of combustion	
	Temperature dependency of ΔH	
	The second law of thermodynamics	Sections 5.1
Week 7:	Heat engines	Sections 5.2 - 5.4
	Entropy	
	Entropy change of an ideal gas	Sections 5.5 - 5.9
	Ideal work and lost work	
	Mathematical statement of the second law	
Week 8:	Thermodynamic properties of fluids	Section 6.1
	Property relations for homogeneous phases	
	2nd Hour Exam	
Week 9:	*Fall Semester Break*	

	Residual properties Residual properties by equations of state Thermodynamic diagrams Generalized property correlations for gases	Sections 6.2 - 6.7
Week 10:	Thermodynamics of flow processes Nozzles Turbines	Sections 7.1, 7.2
Week 11:	Thermodynamics of flow processes Compression processes	Section 7.3
Week 12:	Power cycles Power cycles – Internal combustion engines Refrigeration **3rd Hour Exam**	Section 8.1 Section 8.2
Week 13:	Carnot refrigerator Vapor compression cycle Adsorption refrigeration Heat pump Liquefaction processes	Section 9.1 Section 9.2 Section 9.4 Section 9.5 Section 9.6
Week 14:	Vapor Liquid Equilibrium *Thanksgiving Vacation*	Sections 10.1-10.3
Week 15:	Vapor Liquid Equilibrium	Sections 10.4 – 10.6
Week 16:	Review	

Exams 1-3

Final Exam

John Burke

100

February 4, 2013

CHME 223
EXAM #1
(Open Book)

0

1. [35 pts] A reversible cycle executed by 1 mol of an ideal gas consists of the following steps:
    a. Starting at 600 K and 2 bar, the gas is cooled at constant pressure to 300 K.
    b. From 300 K and 2 bar, the gas is compressed isothermally to 4 bar.
    c. The gas returns to its initial state along a path for which the product PT is constant.

Draw a P-V diagram and calculate the work of the cycle.

0

2. [35 pts] A cylinder with a frictionless piston contains 3 kg of water at 20 C and 10 bar. Heat is added to the cylinder, the water boils and become all steam and the piston moves out until the temperature reaches 300C, while the pressure remains constant at 10 bar. For the 3 kg of fluid find:
    a. The work done by the fluid.
    b. The change in the internal energy of the fluid.
    c. The heat added to the fluid.

3. [30 pts] In some flow problems involving gases it is necessary to evaluate the integral:

0

$$I = \int_{P1}^{P2} V dP \quad \text{(Constant Temperature)}$$

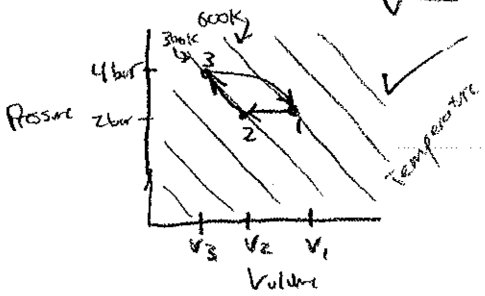
Evaluate this integral for a gas which obeys the truncated virial equation:

$$\frac{PV}{RT} = 1 + \frac{B}{V}$$

where the second virial coefficient B is a function only of T. Use any method you like, but assume that only P1, P2, and T (and, of course, B) are given. That is, your results must be in terms of these quantities.

PV Diagram

①



$V_1 = 24942$

Step 1→2:

State #1: $P = 2$ bar temp $= 600K$

$PV = RT$

$(2\text{ bar})V_1 = (83.14\ \frac{cm^3 bar}{mol})(600K)$ $V_1 = 24942\ cm^3/mol$

Constant P: $\frac{\cancel{P}V_1}{P_1 V_2} = \frac{\cancel{R}T_1}{\cancel{R}T_2}$ $V_1 T_2 = T_1 V_2$

$(24942\ \frac{cm^3}{mol})(300K) = (600K)V_2$; $V_2 = 12471\ cm^3/mol$

$work = -\int pdV = (-2bar)(24942 - 12471\ \frac{cm^3}{mol}) = -24942\ \frac{cm^3 bar}{mol} = work_{1\to2}$

$\boxed{W = +2494.2\ J/mol}$

Step 2→3: Isothermal, so $W = -RT\ln\frac{P_2}{P_1}$

$T = 300K$ $W = (-8.314\ J/molK)(300K)\ln\left(\frac{4bar}{2bar}\right)$

$\boxed{W = +1728.85\ J/mol}$

Step 3→1: $PT = \text{constant}$; $(300K)(4bar) = 1200\ Kbar$

$P = \frac{1200}{T}$; $T = \frac{1200}{P}$

$W = -\int pdV$ Ideal: $PV = RT$ $PV = \frac{R1200}{P}$

$W = -\int \frac{RT}{V}dV$ $P^2V = R1200$; $P = \sqrt{\frac{R1200}{V}}$

Thus, $W = -\int \sqrt{\frac{R1200}{V}}\,dV$ $V_f = 24942\ cm^3/mol$

~~V_i~~ $= 6235.5\ cm^3/mol$

$W = -49884\ \frac{cm^3 bar}{mol} = \boxed{-4988.4\ J/mol}$

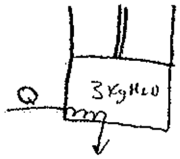
Work Total $= W_{1\to2} + W_{2\to3} + W_{3\to1}$

$W = -2494.2\ \frac{J}{mol} - 1728.85\ \frac{J}{mol} + W_{3\to1}$

$W = -4223.05\ \frac{J}{mol} + W_{3\to1}$

$W = +4223.05\ J/mol - 4988.4\ J/mol$ $\boxed{-9211.45\ J/mol}$

②



initial: 20°C, 10 bar
final: 300°C, 10 bar (All Steam)

Constant Pressure:

From Steam table:
↳ Saturated liquid @ 20°C ⇒ $\left\{ \begin{array}{l} U = 83.86 \text{ kJ/Kg} \\ H = 83.86 \text{ kJ/Kg} \\ V = 1.002 \text{ cm}^3/\text{g} \end{array} \right.$

For Steam @ 300°C, 10 bar (1000 kPa) : $\left\{ \begin{array}{l} U = 2794.2 \text{ kJ/Kg} \\ H = 3052.1 \text{ kJ/Kg} \\ V = 257.98 \text{ cm}^3/\text{g} \end{array} \right.$

(a) work done $= -\int p\,dV$ (P = constant)

$$W = -(10\text{ bar})\left(257.98\ \frac{\text{cm}^3}{\text{g}} - 1.002\ \frac{\text{cm}^3}{\text{g}}\right)$$

$$W = \left(-2569.78\ \frac{\text{bar cm}^3}{\text{g}}\right)\left(\frac{1\text{J}}{10\text{ cm}^3\text{bar}}\right) = \boxed{-256.98\ \text{J/g}}$$

(b) $\Delta U = \left(2794.2\ \frac{\text{kJ}}{\text{Kg}}\right) - \left(83.86\ \frac{\text{kJ}}{\text{Kg}}\right)$; $\boxed{\Delta U = +2710.34\ \frac{\text{kJ}}{\text{Kg}}}$

(c) $\Delta U + \cancelto{0}{\Delta PE} + \cancelto{0}{\Delta KE} = Q + W$

Assumed to be = 0

Thus,

$$2710.34\ \frac{\text{kJ}}{\text{Kg}} = Q + \left(-256.98\ \frac{\text{J}}{\text{g}}\right)\left(\frac{1000\text{g}}{1\text{kg}}\right)\left(\frac{1\text{kJ}}{1000\text{J}}\right)$$

$$Q = (2967.32\ \text{kJ/kg})(3\text{kg}) \quad ; \quad \boxed{Q = +8901.96\ \text{kJ}}$$

③ $T = \int_{P_1}^{P_2} V\,dP$ (Constant Temp)

$d\left(\frac{PV}{RT}\right) = d\left(1 + \frac{B}{V}\right)$; $\frac{1}{RT}\left(d(PV)\right) = B\,d\left(\frac{1}{V}\right)$

tried differentiation, but didn't work

Solution on next Page

Test #1

Try differentiation: and rearrangement

Attempted Solution, but failed

$$\frac{PV}{RT} = 1 + \frac{B}{V}$$

$$\left(PV = RT + \frac{BRT}{V}\right) \times V \quad ; \quad PV^2 = RTV + BRT$$

$$d(PV^2) = d(RTV + BRT)$$

$$V^2 dP + 2VP\,dV = RT\,dV$$

$$V^2 dP = (RT - 2VP)\,dV$$

$$dP = \left(\frac{RT}{V^2} - \frac{2P}{V}\right)dV$$

/OR/

Solution

$$\frac{1}{RT}(P) = \frac{1}{V} + \frac{B}{V^2} \quad ✓ \quad (B)(V^{-2})$$

$$\frac{1}{RT}\,dP = -\frac{1}{V^2} - \frac{2B}{V^3}$$

$$dP = RT\left[-\frac{1}{V^2} - \frac{2B}{V^3}\right]dV \quad ✓ \quad (\text{and}) \quad I = \int_{P_1}^{P_2} V\,dP$$

Thus:

$$I = \int_{V_1}^{V_2} RT\left[-\frac{1}{V} - 2B(V)^{-2}\right]dV$$

$$I = RT\left[-\ln(V) + 2B(V)^{-1}\right]\Big|_{V_1}^{V_2} \Rightarrow RT\left[-\ln(V) + \frac{2B}{V}\right]\Big|_{V_1}^{V_2}$$

$$☆ \quad I = RT\left[-\ln(V_2) + \frac{2B}{V_2}\right] - RT\left[-\ln(V_1) + \frac{2B}{V_1}\right] \quad ☆ \quad ✓$$

Then From viral equation: $\frac{PV^2}{RT} = V + B$; $PV^2 - VRT - RTB = 0$

Thus $V = \dfrac{RT \pm \sqrt{(RT)^2 + 4(P)(RTB)}}{2P^2}$ ✓ (now sub. in for V_2 and V_1)

$$\text{Thus,} \quad I = RT\left[-\ln\left(\frac{RT \pm \sqrt{(RT)^2 + 4(P_2)(RTB)}}{2P_2^2}\right) + \frac{2B}{\left(\frac{RT \pm \sqrt{(RT)^2 + 4(P_2)(RTB)}}{2P_2^2}\right)}\right] \quad \ldots \text{continued}$$

$$- RT\left[-\ln\left(\frac{RT \pm \sqrt{(RT)^2 + 4(P_1)(RTB)}}{2P_1^2}\right) + \frac{2B}{\frac{RT \pm \sqrt{(RT)^2 + 4(P_1)(RTB)}}{2P_1^2}}\right]$$

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95

February 28, 2013

CHME 223
EXAM #2
(Open Book)

1\. [50 pts] A fuel gas consisting of 90 mole percent methane and 10 mole percent nitrogen is burned with 30 percent excess air in a continuous water heater. Both fuel gas and air enter dry at 25 C and atmospheric pressure. Water is heated at a rate of 34.0 kg/s from 25 C to 95 C. The flue gases leave the heater at 210 C. Of the entering methane, two-thirds burns to carbon dioxide and one-third burn to carbon monoxide. What volumetric flow rate of fuel gas is required if there are no heat losses to the surroundings. Assume constant heat capacities for the flue gases as given in Table C. 1 at the ideal state.

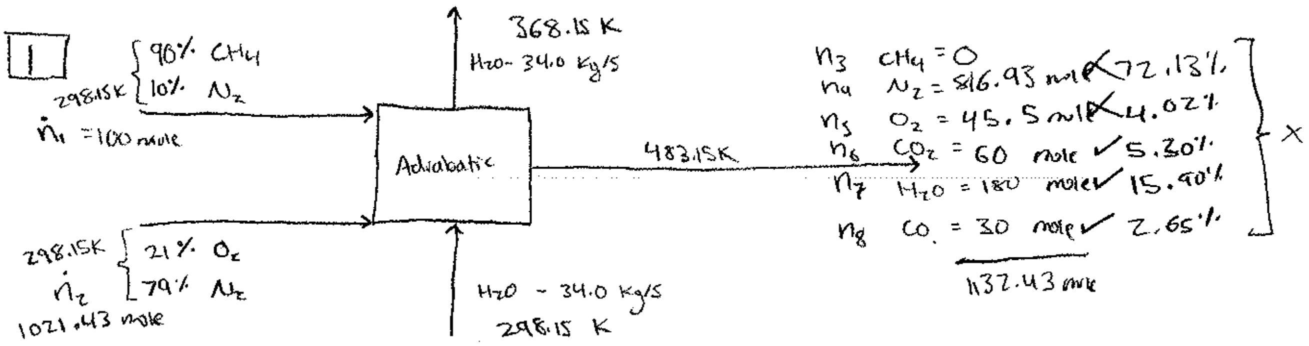
-5

2\. [30 pts] A reversible engine takes in 1200 BTU from a large thermal reservoir at T_1 and discards 920 BTU to another reservoir T_2 where T_2 is 40 F cooler than T_1. Find the work in BTU done by the engine and temperatures T_1 and T_2.

0

3\. [20 pts] An egg initially at rest, is dropped onto a concrete surface; it breaks. Prove that the process is irreversible ($\Delta S > 0$). In modeling this process treat the egg as the system, and assume the passage of sufficient time for the egg to return to its initial temperature.

0



<u>Reaction:</u>

$$CH_{4(g)} + 2\,O_{2(g)} \longrightarrow CO_{2(g)} + 2\,H_2O_{(g)}$$

$$CH_{4(g)} + \tfrac{3}{2}\,O_{2(g)} \longrightarrow CO_{(g)} + 2\,H_2O_{(g)}$$

REQ'D O_2 IS BASED ON COMPLETE COMB.

<u>Cp-values:</u> C_p/R

$H_2O_{(l)}$ = 9.069 $CH_{4(g)}$ = 4.217 $CO_{2(g)}$ = 4.467 $O_{2(g)}$ = 3.535
$H_2O_{(g)}$ = 4.038 $N_{2(g)}$ = 3.502 $CO_{(g)}$ = 3.507

<u>Energy Balance:</u> $W_s = 0$; $Q = 0$

$$\Delta H_{H_2O} + \Delta H_{gas} = 0$$

<u>ΔH_{H_2O}:</u>

$$\Delta H_{H_2O} = R\int C_p\,dT = (368.15\text{K} - 298.15\text{K})(9.069)(8.314\ \text{J/mol K}) = 5.278\ \frac{\text{KJ}}{\text{mol}}$$

$$\text{moles } H_2O = \left(34\ \frac{\text{Kg}}{\text{s}}\right)\left(\frac{1\ \text{Kmole}}{18\ \text{Kg}}\right)\left(\frac{1000\ \text{mole}}{1\ \text{Kmole}}\right) = 1888.9\ \frac{\text{mole}}{\text{s}}\ H_2O$$

$$\Delta H^t_{H_2O} = \left(5.278\ \frac{\text{KJ}}{\text{mole}}\right)\left(1888.9\ \text{mole/s}\right) = +9969.6\ \text{KJ/s}\ ✓$$

<u>Mass Balance Gas:</u> Basis = 100 mole fuel ($\dot{n}_1$)

Feed 2/3 → CO_2 ; $100\text{ mole}(0.90)(2/3)\left(\frac{1\text{mole}}{1\text{mole}}\right) = 60\text{ mole } CO_2 = n_6$ ✓
Feed 1/3 → CO ; $100\text{ mole}(0.90)(1/3)\left(\frac{1\text{mole}}{1\text{mole}}\right) = 30\text{ mole } CO = n_8$ ✓

30% Excess Air : theoretical : $60\text{ mole } CH_4\left(\frac{2}{1\text{mole}}\right) = 120\text{ mole } O_2$
$30\text{ mole } CH_4\left(\frac{3/2}{1\text{mole}}\right) = 45\text{ mole } O_2$ → 165 mole O_2 = 785.71 mole Air

thus, $785.71(1.30) = 1021.43$ mole Air $= n_2$

N_2 balance: $1021.43\text{ mole}(0.79) + 100\text{ mole}(0.10) = n_4$; $n_4 = 816.93$ mole

H balance: $100\text{ mole}(0.9)(4) = 2n_7$; $n_7 = 180$ mole

O balance: $1021.43\text{ mole}(0.21)2 = 2n_5 + 60\text{ mole}(2) + 180\text{ mole}(1) + 30\text{ mole}$
$n_5 = 49.5$ mole

	n_{in}	H_{in}	n_{out}	H_{out}
$CH_{4(g)}$	90 mole	0 (Reference)	0	—
$N_{2(g)}$	816.93 mole	0	816.93 mole	$\hat{H}_1 = 5.386$ kJ/mol
$O_{2(g)}$	214.5 mole	0	45.5 mole	$\hat{H}_2 = 5.437$ kJ/mol
$CO_{2(g)}$	0	—	60 mole ✓	$\hat{H}_3 = -386.64$ kJ/mol
$CO_{(g)}$	0	—	30 mole ✓	$\hat{H}_4 = -105.13$ kJ/mol
$H_2O_{(g)}$	0	—	180 mole ✓	$\hat{H}_5 = -235.61$ kJ/mol

Reference Temp = 298.15 K (25°C)

Heats of Formation Method:

$$\hat{H}_1 = \int_{298.15K}^{483.15K} (3.502)(8.314 \text{ J/mol K})\, dT + 0 \text{ formation}$$

$\hat{H}_1 = 5.386$ kJ/mol ✓

$$\hat{H}_2 = (185 \text{ K})(3.535)(8.314 \text{ J/mol K}) + 0 \text{ formation}$$

$\hat{H}_2 = 5.437$ kJ/mol ✓

$$\hat{H}_3 = (185 \text{ K})(4.467)(8.314 \text{ J/mol K}) + (\overset{\text{formation}}{-393,509} \text{ J/mol})$$

$\hat{H}_3 = -386.64$ kJ/mol ✓

$$\hat{H}_4 = (185 \text{ K})(3.507)(8.314 \text{ J/mol K}) + (\overset{\text{formation}}{-110,525} \text{ J/mol})$$

$\hat{H}_4 = -105.13$ kJ/mol ✓

$$\hat{H}_5 = (185 \text{ K})(4.038)(8.314 \text{ J/mol K}) + (\overset{\text{formation}}{-241,818} \text{ J/mol})$$

$\hat{H}_5 = -235.61$ kJ/mol ✓

Product: $\Delta H = -64114.73 \dfrac{\text{kJ}}{100 \text{ mole fuel feed}} = -641.1473$ kJ/mole fuel feed

Overall: $9969.6 \text{ kJ/s} = \left(641.1473 \dfrac{\text{kJ}}{\text{mole feed}}\right)\dot{n}_{feed}$

$\dot{n}_{feed} = 15.55$ mole/s

or

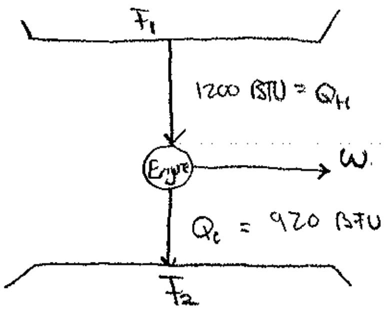
→ 13.99 mole/s $CH_{4(g)}$ ($\cancel{98.6}$ $\frac{cm^3}{mole}$) = 1379.41 $\frac{cm^3}{s}$ CH_4

→ 1.555 mole/s $N_{2(g)}$ ($\cancel{89.2}$ $\frac{cm^3}{mole}$) = 138.71 $\frac{cm^3}{s}$ N_2

$$\boxed{\text{Total flow} = 1518.12\ \cancel{cm^3}/s}$$

Another solution is on page 5/// where Carnot is not assumed

2



$T_1 - T_2 = 40°F$

or $T_1 - T_2 = 40R$

$|W| = |1200\ BTU| - |920\ BTU|$ $\quad |W| = 280\ BTU$

- Thus, engine does 280 BTU of work ✓

Also, $\dfrac{|Q_H|}{|Q_c|} = \dfrac{T_1}{T_2}$ and $T_1 - T_2 = 40°F$

or $T_1 = T_2 + 40°F$

$\dfrac{1200\ BTU}{920\ BTU} = \dfrac{40R + T_2}{T_2}$; $\quad 1.3043 T_2 = 40R + T_2$

$$\boxed{T_2 = 131.45R} ✓$$

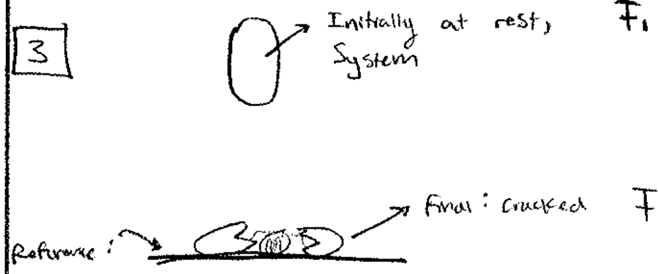
- Check Answer:

$\dfrac{1200\ BTU}{920\ BTU} \overset{?}{=} \dfrac{171.45R}{131.45\ R}$ = yes///

$T_1 - 131.45R = 40R$

$$\boxed{T_1 = 171.45R} ✓$$

3



T_1
T_2 $\Rightarrow T_1 = T_2$

- Taking the benefit of the doubt, I assume reversible process!

- Since Temp is constant ΔU (or ΔH) ≈ 0

$\cancelto{0}{\Delta U} + \cancelto{0}{\Delta KE} + \Delta PE = Q + \cancelto{0}{W}$

$\Delta KE = 0$ (since starting from rest, ending at rest)

$W = 0$ (only work is in form of gravitational work, or ΔPE)

- Thus, $\Delta PE = Q$ (Taking ground as reference)

$mg\cancelto{0}{y_f} - mgy_i = Q$; $\quad -mgy_i = Q$ ✓

- Since $g = (-)$ or rather depending up assumed directions

$$|-mgy_i| = Q$$

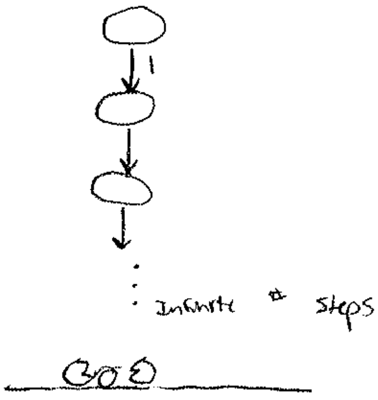
$$|mgy_i| = Q$$

- Also, $\Delta S^t_{System} = \int \frac{dQ_{rev}}{T}$, which reduces to:

$$\boxed{\Delta S^t_{Surroundings} = \frac{Q}{T} = \frac{|mgy_i|}{T} \quad \text{(Since } T \text{ is constant)}}$$ ✓

$$|mgy_i| = Q$$

- It would be tempting to conclude that this Q value is equivalent to Q for egg. However, I assumed reversible process! Therefore, using an infintesmal amount of steps, $Q_{egg} = 0$. ↖reversible



Thus, $\Delta S_{egg} = \int \frac{Q_{rev}}{T} = 0$ ✓

Thus,

$$\Delta S_6 = \Delta S^t_{egg} + \Delta S^t_{surroundings}$$

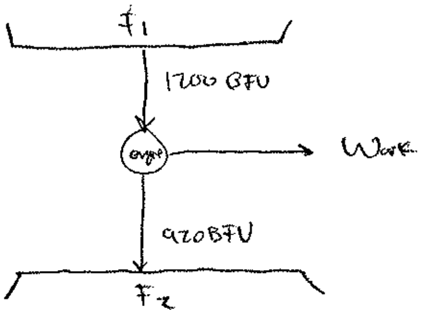
$$\Delta S_6 = 0 + \frac{|mgy_i|}{T} \qquad \boxed{\Delta S_6 = \frac{|mgy_i|}{T}}$$ ✓

- Therefore, since both $|mgy_i|$ and T are positive (since absolute temperature scale is used)

$$\boxed{\Delta S_6 > 0}$$ ✓

Checked

2 Reversible, so $\Delta S = 0$



Energy Balance:

$$\cancel{\Delta U}^{0} + \cancel{\Delta PE}^{0} + \cancel{\Delta KE}^{0} = Q + W$$

Work = 1200 BTU − 920 BTU

$$\boxed{\text{Work} = 280 \text{ BTU done by engine}}$$

$$\Delta S = 0 = \frac{Q_{T_1}}{T_1} + \frac{Q_{T_2}}{T_2}$$

$$0 = \frac{-1200 \text{ BTU}}{T_1} + \frac{920 \text{ BTU}}{T_2}$$

$T_1 - T_2 = 40R$

$T_1 = 40 + T_2$

$$0 = \frac{-1200 \text{ BTU}}{40 + T_2} + \frac{920 \text{ BTU}}{T_2}$$

$$\frac{1200}{40+T_2} = \frac{920}{T_2} \; ; \quad 1200\,T_2 = 36800 + 920\,T_2$$

$$\boxed{T_2 = 131.43\ R}$$

$T_1 = 40 + 131.43^{\circ}F$

$$\boxed{T_1 = 171.43\ R}$$

SAME AS when Assumed to be Carnot engine

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95

April 4, 2013

CHME 223
EXAM #3
(Open Book)

1. Propane gas at 71 C (160 F) and 101 kPa (14.6 psia) is compressed isothermally to 1700 kPa (246 psia). Estimate ΔH and ΔS for the process by:
   - 0 a) [25 pts] Generalized second-virial-coefficient correlation.
   - 0 b) [25 pts] Generalized Lee/Kesler correlation.
   - 0 c) [25 pts] The attached PH diagram for propane. Trace the path of the compression on this diagram. Change the units for ΔH and ΔS to J/mol for ΔH and J/mol/K for ΔS and compare your results for parts a, b, and c.

Notes:
In its initial state, propane gas may be assumed to be ideal gas.
The critical properties of propane are: $T_C = 369.8$ K, $P_C = 42.48$ bar, $\omega = 0.152$.

2. [15 pts] Two schemes are proposed for the reduction in pressure of a gas from 400 K and 20 bar to a pressure of 2 bar in a steady flow process.
   6
   - a) Pass it through a throttle valve.
   - b) Send it through an adiabatic expander (turbine) of 70% efficiency.

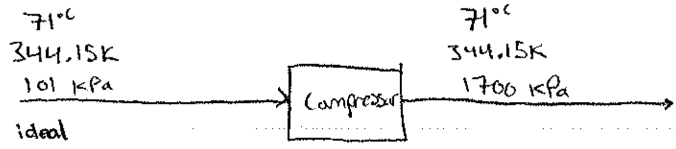
   Explain which process results in a lower exit temperature for the gas?

3. [10 pts] For steam expanding isentropically in a nozzle from 1400 kPa, 320 C, and 30 m/s to a discharge pressure of 200 kPa where its velocity is 700 m/s, what type of nozzle is used. Explain.
   4

$C = 31.6\sqrt{\gamma R T}$

$C = 596$ m/s

①



$T_R = \frac{344.15K}{369.8K} = 0.931$

$\omega = 0.152$

Final $\left\{ P_r = \frac{17 \text{ bar}}{42.48 \text{ bar}} = 0.400 \right.$

In general: $\Delta S = \Delta S_{ideal} + \Delta S^R$

$\Delta H = \Delta H_{ideal} + \Delta H^R$

$\boxed{A}$ initially: $S_1^R = H_1^R = 0$

finally: $B^0 = 0.083 - \frac{0.422}{0.931^{1.6}} = -0.390$

$B^1 = 0.139 - \frac{0.172}{0.931^{4.2}} = -0.0932$

$\frac{dB^0}{dT_r} = \frac{0.675}{0.931^{2.6}} = 0.813$

$\frac{dB^1}{dT_r} = \frac{0.722}{0.931^{5.2}} = 1.047$

$H_2^R = (8.314 \text{ J/mol·K})(369.8 K)\left[-0.39 - 0.931(0.813) + 0.152(-0.0932 - 0.931(1.047))\right] \times (0.400)$

$\underline{\underline{H_2^R}} = -1610.1 \text{ J/mol}$

$S_2^R = (8.314 \text{ J/mol·K})(-0.400)\left[0.813 + 0.152(1.047)\right]$

$\underline{\underline{S_2^R}} = -3.23 \text{ J/mol·K}$

·Isothermal So $\Delta H_{ideal} = 0$ J/mol

$\Delta S_{ideal} = R\left[\cancelto{0}{\int_{T_0}^{T} \frac{C_p^{ig}}{R} \frac{dT}{T}} - \ln \frac{P}{P_0}\right] = -R \ln \frac{P}{P_0}$

$\Delta S_{ideal} = -8.314 \ln\left(\frac{1700 \text{ kPa}}{101 \text{ kPa}}\right) = -23.48 \text{ J/mol·K}$

$\Delta H = 0 + (-1610.1 \text{ J/mol}) + 0 \quad \boxed{\Delta H = -1610.1 \text{ J/mol}}$

$\Delta S = -23.48 \text{ J/mol·K} - 3.23 \text{ J/mol·K} \quad \boxed{\Delta S = -26.71 \text{ J/mol·K}}$

B $\Delta S_{Ideal} = -23.48 \ J/mol \cdot K$ $\Delta H_{ideal} = 0 \ J/mol$

- Again initial state is ideal so $H_1^R = S_1^R = 0$

Final State:

$$\frac{H^R}{RT_c} = \frac{(H^R)^0}{RT_c} + \omega \frac{(H^R)^1}{RT_c} \qquad \frac{S^R}{R} = \frac{(S^R)^0}{R} + \omega \frac{(S^R)^1}{R}$$

- At $T_R = 0.931$ and $P_R = 0.400$: (TABLE Gives)

$$\frac{(H^R)^0}{RT_c} = -0.544 \qquad \frac{(H^R)^1}{RT_c} = -0.6085$$

Thus, $H_2^R = (8.314 \ J/mol \cdot K)(369.8 K)[-0.544 + 0.152(-0.6085)]$

$H_2^R = -1956.91 \ J/mol$

$$\frac{(S^R)^0}{R} = -0.406 \qquad \frac{(S^R)^1}{R} = -0.5892$$

$S_2^R = 8.314 \ J/mol \cdot K \left[-0.406 + 0.152(-0.5892)\right]$

$S_2^R = -4.12 \ J/mol \cdot K$

$$\boxed{\Delta H = -1956.91 \ J/mol}$$

$\Delta S = -23.46 \ J/mol \cdot K - 4.12 \ J/mol \cdot K$

$$\boxed{\Delta S = -27.58 \ J/mol \cdot K}$$

C From Graph:

Initial: $H_1 = -618 \ \frac{BTU}{lb_m}$

$H_2 = -635 \ \frac{BTU}{lb_m}$

$\Delta H = -17 \ \frac{BTU}{lb_m}$

$$\Delta H = \left(-17 \ \frac{BTU}{lb_m}\right)\left(\frac{2.20462 \ lb_m}{10^3 \ g}\right)\left(\frac{44.097 \ g}{1 \ mole}\right)\left(\frac{1 J}{9.47831 \times 10^{-4} \ BTU}\right) = \boxed{-1743.66 \ \frac{J}{mol} = \Delta H}$$

$S_1 = 1.52 \ BTU/lb_m \cdot R$

$S_2 = 1.375 \ \frac{BTU}{lb_m \cdot R}$

$\Delta S = -0.145 \ \frac{BTU}{lb_m \cdot R}$

$$\Delta S = -0.145 \frac{BTU}{lbm \cdot R}\left(\frac{2.20462\ lbm}{10^3 g}\right)\left(\frac{44.097 g}{1 mole}\right)\left(\frac{1 J}{9.47831 \times 10^{-4} BTU}\right)\left(\frac{1.8 R}{1 K}\right)$$

$$\boxed{\Delta S = -26.77\ J/mol \cdot K}$$

Final Results:

	ΔH	ΔS
A	−1610.1 J/mol	−26.71 J/mol·K
B	−1956.91 J/mol	−27.58 J/mol·K
C	−1743.66 J/mol	−26.77 J/mol·K

2

- For throttle valve $\Delta H = 0$
- For expander $Q = 0$

- For valve (throttle) the temperature will be slightly lower, since the only contributing factor to temp change is from non-ideal portion of system. ($\Delta T = 0$ if $\Delta H = 0$ for ideal part).

- For expander, $\Delta H < 0$ and thus a larger temperature decrease will be seen. (i.e. both ideal and non-ideal portions of system contribute to temperature drop)
THIS IS CONTRIBUTED TO THE WORK DONE BY THE TURBINE

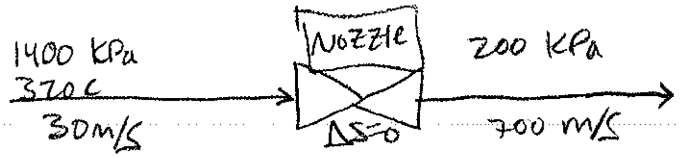
Adiabatic Expander: $\Delta H = -|W|$ $\Delta H < 0$ [meaning relatively low exit temp]

↳ where, $0 > \Delta H = \Delta H_{ideal} + H_2^R - H_1^R$

Throttle Valve: $\Delta H = 0$

$$0 = \Delta H = \underbrace{\Delta H_{ideal}}_{\text{very small since } (T_2 - T_1) \text{ is small due to non-ideal portion}} + H_2^R - H^R$$

3



· The nozzle has to be a <u>converging</u> nozzle.

Since $u_{Inlet} = 30$ m/s , this means that $M < 1$.

If the nozzle were diverging, then the speed would decrease ($du/dx < 0$); however, the speed is increasing ($du/dx > 0$) and hence it must be a <u>converging</u> nozzle.

$u_2 = 700$ m/s $> C$

CONVERGING – DIVERGING

Final Point

6220

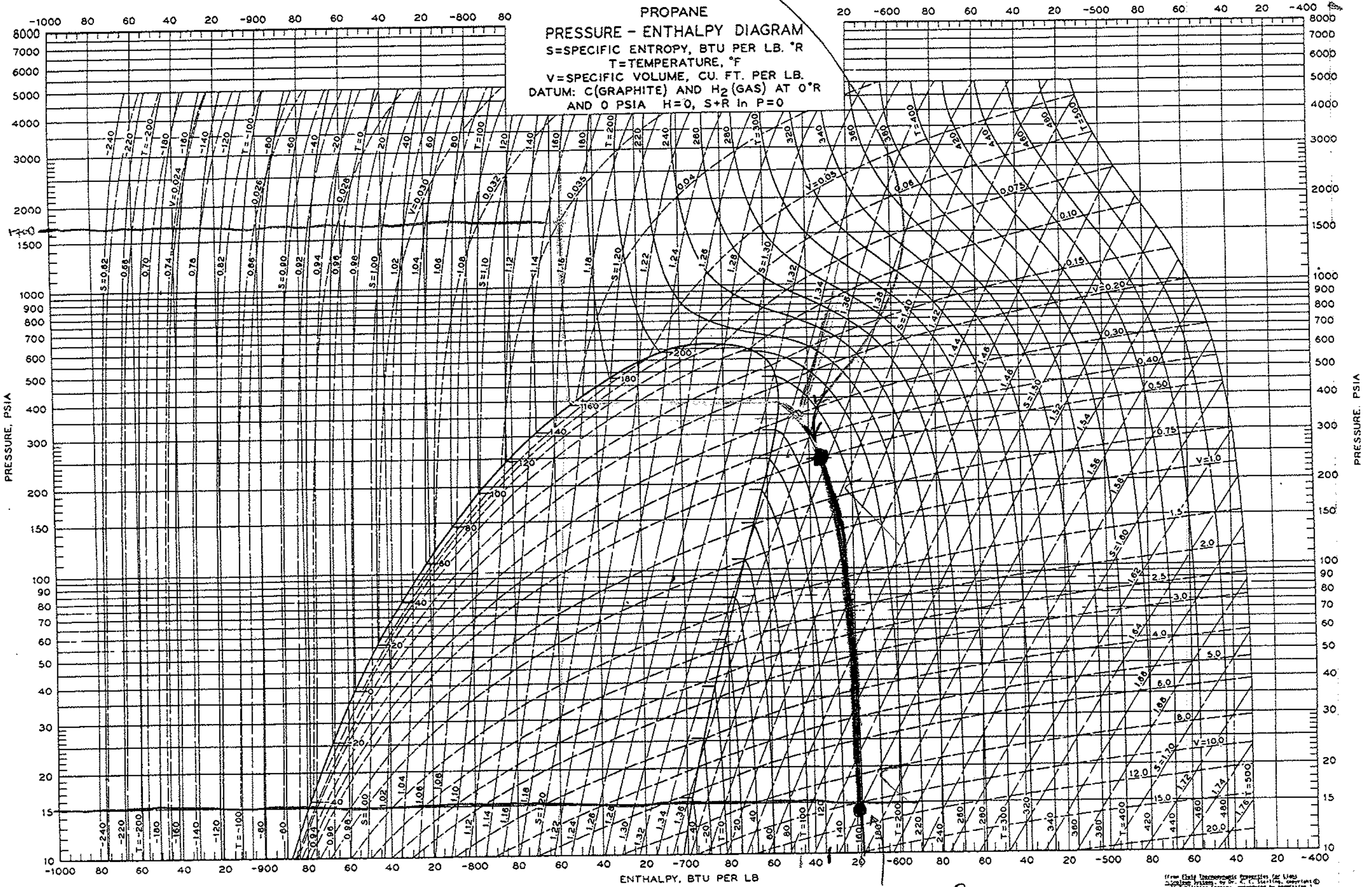


FIG. 17-6
PROPANE
PRESSURE - ENTHALPY DIAGRAM
S=SPECIFIC ENTROPY, BTU PER LB. °R
T=TEMPERATURE, °F
V=SPECIFIC VOLUME, CU. FT. PER LB.
DATUM: C(GRAPHITE) AND H_2(GAS) AT 0°R
AND 0 PSIA H=0, S+R ln P=0

Starting Point

$H_2 \simeq -635$ BTU/lb
$S_2 \simeq 1.375$ BTU/lbm R

(From Fluid Thermodynamic Properties for Light Petroleum Systems, by Dr. K. E. Starling, copyright © Gulf Publishing Company, reproduced by permission.)

94257244

100 BURKE

April 30, 2013

CHME 223
FINAL EXAM
(Open book)

1. [30 pts] Steam enters the turbine of a power plant at 820 F and 500 psia. It expands to a saturated vapor at a pressure of 20 psia.
   - 0 a) [10 pts] Locate these two points on the attached Mollier diagram. Compare your values with values from steam table (Table F.4).
   - 0 b) [10 pts] How much work (Btu) does the turbine produce per pound of steam? What is the power output (HP) if the steam flow rate is 4 lb/sec?
   - 6 c) [10 pts] What is the efficiency of the turbine relative to an isentropic expansion?

2. [20 pts] Determine the maximum amount of work (ideal work) obtained in a flow process from 1 kg of steam at 3000 kPa and 450 C for surrounding conditions of 300 K and 101.3 kPa.

0

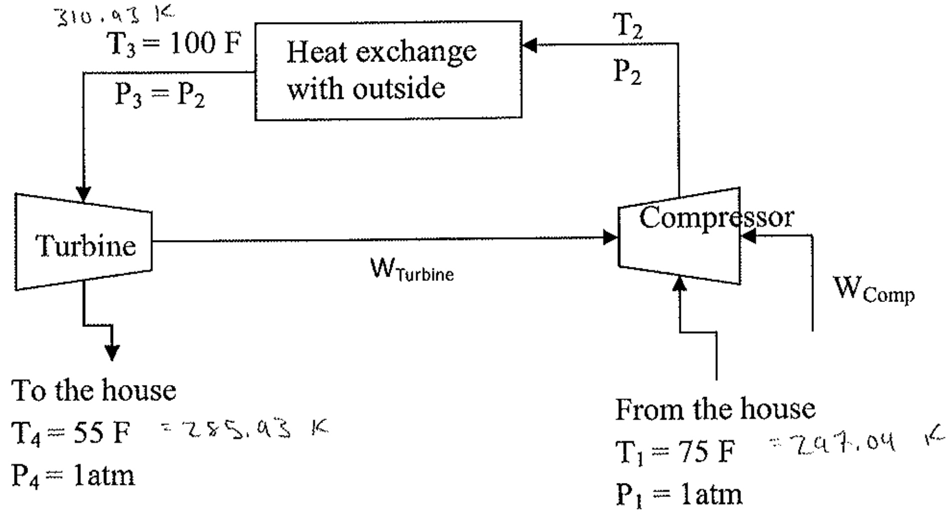
final sat. liquid @ temp of surroundings

3. [20 pts] Prove that the outlet temperature for an actual (irreversible) adiabatic process is greater than that for a reversible adiabatic process for a process consisting of a single gas stream entering the process at T_1 and P_1 and leaving at T_2 and P_2. Assume the gas is ideal with constant heat capacity.

0

4. [30 pts] The following process has been suggested for air-conditioning a house. In the summer, air from the house at 75 F is compressed adiabatically, cooled to 100 F by heat exchange with the outside air, and then expanded adiabatically through a turbine. The work from the turbine is applied to the compression step. The air leaves the turbine at 55 F and enters the house's air handling ductwork. Calculate the coefficient of performance for the case when both compressor and turbine operate reversibly. Assume air an ideal gas for which $C_P = (7/2)\,R$ and $C_V = (5/2)\,R$.

6



1 (a) From Mollier:
initial = 1423 BTU/lbm
Final = 1155 BTU/lbm

I chose to compare enthalpies

From steam table:
initial = 1423.48 BTU/lbm
Final = 1156.3 BTU/lbm

(b) For work: $\Delta H = W$

$W_{Table} = (1156.3 \text{ BTU/lbm} - 1423.48 \text{ BTU/lbm})$

$\boxed{W_{Table} = -267.18 \text{ BTU/lbm}}$

$W_{mollier} = 1155 \text{ BTU/lbm} - 1423 \text{ BTU/lbm}$

$\boxed{W_{mollier} = -268.0 \text{ BTU/lbm}}$

For Power output, I will use W_{TABLE}:

$$W_{out} = \left(-267.18 \frac{\text{BTU}}{\text{lbm}}\right)\left(4 \frac{\text{lbm}}{\text{s}}\right)\left(\frac{1.34102 \text{ hp}}{0.947831 \text{ BTU/s}}\right)$$

$\boxed{W_{out} = -1512.06 \text{ hp}}$

(c) From mollier $(H_2)_S = 1115$ BTU/lbm

$(\Delta H)_S = (1115 \text{ BTU/lbm} - 1423.48 \text{ BTU/lbm})$

$(\Delta H)_S = -308.48$ BTU/lbm

$$\eta = \frac{-267.18 \text{ BTU/lbm}}{-308.48 \text{ BTU/lbm}}$$

$\boxed{\eta = 0.866}$

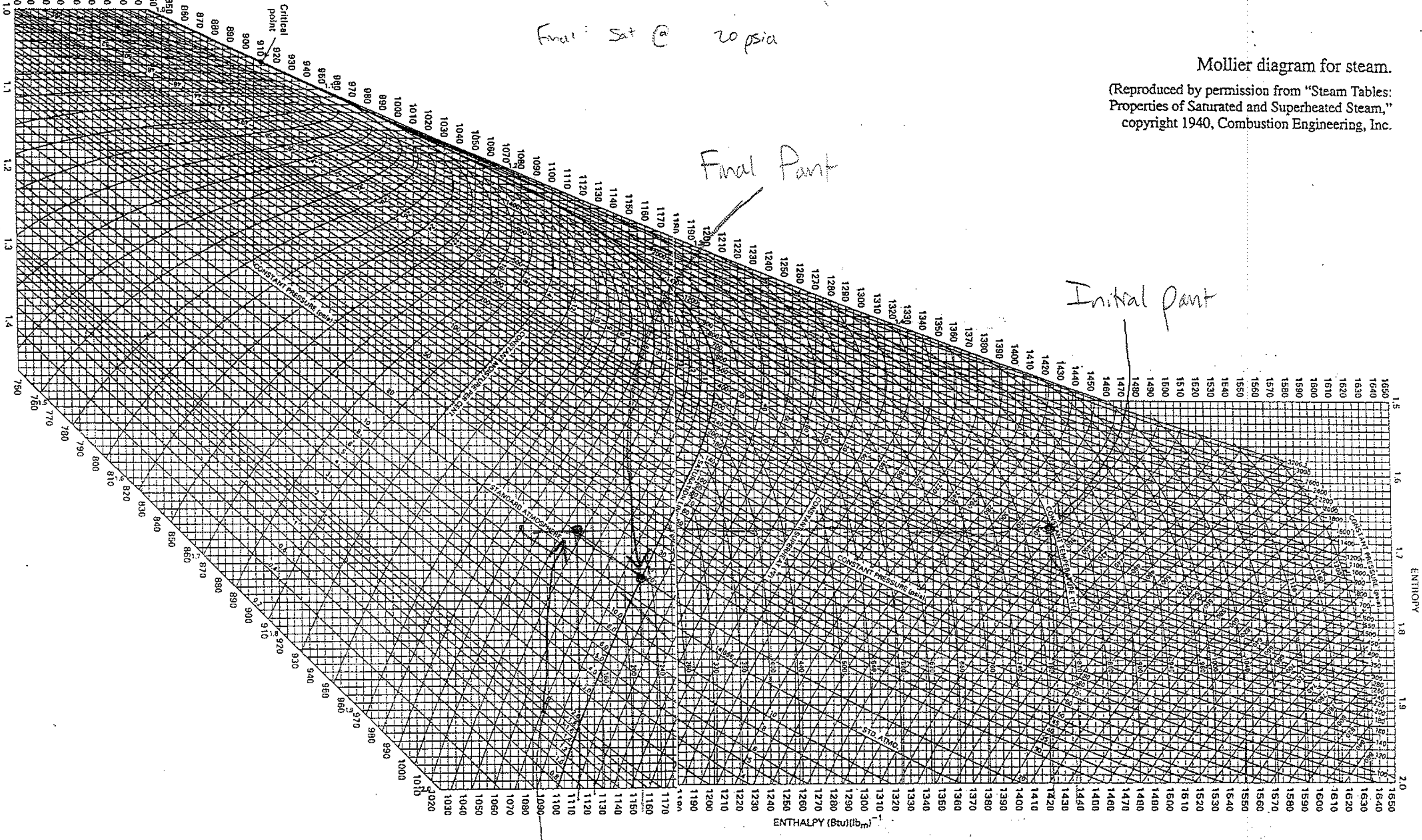
94257244

initial: 820f and 500 psia

Final: Sat @ 20 psia

Mollier diagram for steam.

(Reproduced by permission from "Steam Tables: Properties of Saturated and Superheated Steam," copyright 1940, Combustion Engineering, Inc.

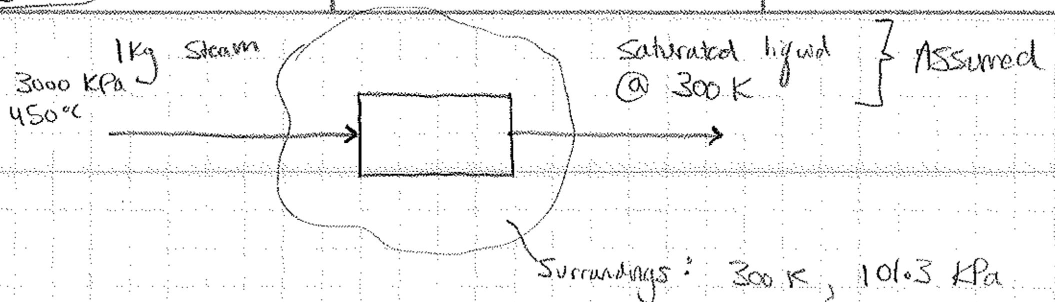


Final Pant

Initial pant

isentropic expansion final position

2



$W_{ideal} = \Delta H - T_o \Delta S$; $T_o = 300\,K$

From Steam Table:

Initial State		Final State
$H_i = 3344.6$ KJ/Kg ✓	from interpolation	$H_f = 112.47$ KJ/Kg ✓
$S_i = 7.0854$ KJ/Kg·K ✓		$S_f = 0.39282$ KJ/Kg·K

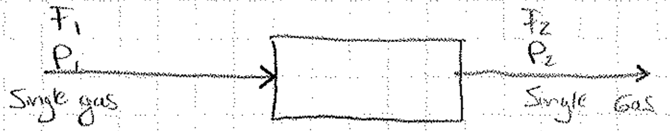
$\Delta H = (112.47\ KJ/Kg - 3344.6\ KJ/Kg)\,1Kg$ $\quad \underline{\Delta H} = -3232.13\ KJ$ ✓

$\Delta S = (0.39282\ KJ/Kg\cdot K - 7.0854\ KJ/Kg\cdot K)\cdot 1Kg$ $\quad \underline{\underline{\Delta S}} = -6.6926\ \frac{KJ}{K}$ ✓

$W_{ideal} = -3232.13\ KJ - (300\,K)(-6.6926\ KJ/K)$ ✓

$\boxed{W_{ideal} = -1224.35\ KJ}$ ✓

3



For reversible Adiabatic: $\Delta S_{revers} = 0$ and $\frac{\Delta S}{R} = \int_{T_1}^{T_2} \frac{Cp^{i.g.}}{R}\frac{dT}{T} - \ln\frac{P_2}{P_1}$

Thus, $$0 = \int_{T_1}^{T_{2}} \frac{Cp^{i.g.}}{R}\frac{dT}{T_{revers}} - \ln\frac{P_2}{P_1}$$

For irreversible Adiabatic: $\Delta S_{irr} > 0$ (for process to take place)

Thus, $$0 < \int_{T_1}^{T_{2-revers}} \frac{Cp^{i.g.}}{R}\frac{dT}{T} - \ln\frac{P_2}{P_1}$$

↳ Now notice that irreversible ΔS must be greater than reversible, so the following expression holds:

$$\Delta S_{irr} - \Delta S_{revers} > 0$$

$$\left[\int_{T_1}^{T_{2-irr}} \frac{Cp^{i.g.}}{R}\frac{dT}{T} - \ln\frac{P_2}{P_1}\right] - \left[\int_{T_1}^{T_{2-revers}} \frac{Cp^{i.g.}}{R}\frac{dT}{T} - \ln\frac{P_2}{P_1}\right] > 0$$

↳ reduction leads to:

$$\int_{T_1}^{T_{2-irr}} \frac{Cp^{i.g.}}{R}\frac{dT}{T} - \int_{T_1}^{T_{2-revers}} \frac{Cp^{i.g.}}{R}\frac{dT}{T} > 0$$

↳ Assuming $Cp^{i.g.}$ to be constant (since is the same for both expressions)

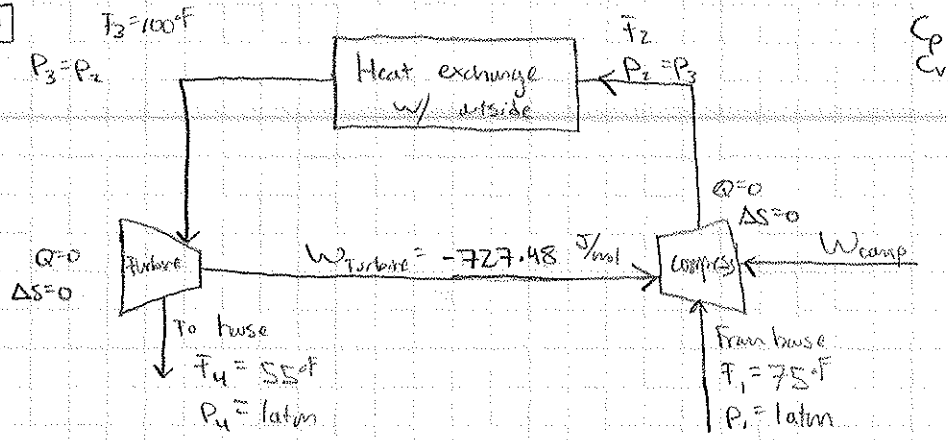
$$\frac{Cp^{i.g.}}{R}\ln\left(\frac{T_{2-irr}}{T_1}\right) - \frac{Cp^{i.g.}}{R}\ln\left(\frac{T_{2-revers}}{T_1}\right) > 0$$

Thus, $$\ln\left(\frac{T_{2-irr}}{T_1}\right) - \ln\left(\frac{T_{2-revers}}{T_1}\right) > 0$$

Finally: $\frac{T_{2-irr}}{T_1} > \frac{T_{2-revers}}{T_1}$ (or) $\boxed{T_{2-irr} > T_{2-revers}}$

Thus, T_2 irreversible must be greater than T_2 reversible.

$\boxed{4}$



$C_p = 7/2 R$
$C_v = 5/2 R$

$$\omega = \frac{|Q_c|}{W_{net}}$$

<u>For turbine:</u> $\Delta S = 0$; $\Delta H = W_{Turbine}$; $Q = 0$

$$W_{Turbine} = \int_{T_3}^{T_4} C_p \, dT = \left(\int_{310.93K}^{285.93K} 7/2 (8.314 \text{ J/mol·K}) \, dT \right)$$

$$W_{Turbine} = -727.475 \text{ J/mol} \checkmark$$

<u>For Heat exchang w/ outside:</u> $W = 0$; $\Delta H = Q_c$

$$Q_H = \int_{T_2}^{T_3} 7/2 R \, dT \quad ; \quad Q_c = \tfrac{7}{2} R [310.93 \text{ K} - T_2]$$

<u>For compressor:</u> $Q = 0$; $\Delta S = 0$; $\Delta H = -W_{turbine} + W_{comp}$

$$+727.475 \text{ J/mol} + W_{comp} = \int_{297.04K}^{T_2} (7/2 R) \, dT$$

$$+727.475 \text{ J/mol} + W_{comp} = \tfrac{7}{2} R [T_2 - 297.04 \text{ K}]$$

$$W_{comp} = 7/2 R [T_2 - 297.04 K] - 727.475 \text{ J/mol}$$

Calculated twice by accident

<u>Overall System:</u> $W_{comp} + Q_c = \Delta H_{syst}$

$$\Delta H_{sys} = \int_{297.03K}^{285.93K} (7/2 R) \, dT \qquad \Delta H_{sys} = -323.0 \text{ J/mol}$$

To Find T_2: compressor is reversibly adiabatic ($\Delta S = 0$)

$$\frac{\Delta S}{R} = 0 = \int_{297.04\,K}^{T_2} \frac{7}{2}\frac{dT}{T} - \ln\left(\frac{P_2}{1atm}\right)$$

$$0 = \frac{7}{2}\ln\left(\frac{T_2}{297.04K}\right) - \ln\left(\frac{1.341\ atm}{1atm}\right) \quad ; \quad \underline{\underline{T_2}} = 323.02K$$

✓

To Find P_2: turbine is reversibly adiabatic ($\Delta S = 0$)

$$\frac{\Delta S}{R} = 0 = \int_{310.93\,K}^{285.93K} \frac{7}{2}\frac{dT}{T} - \ln\left(\frac{1atm}{P_2}\right)$$

$$0 = -0.2934 - \ln\left(\frac{1atm}{P_2}\right) \qquad \underline{\underline{P_2}} = 1.341\ atm$$

✓

W_{comp}:

$$W_{comp} = \frac{7}{2}R\left[323.02\,K - 297.04\,K\right] - 727.475\ J/mol$$

$$\underline{\underline{W_{comp}}} = +28.52\ J/mol$$

✓

Q_H:

$$Q_H = \frac{7}{2}R\left[310.93\,K - 323.02\,K\right]$$

$$\underline{\underline{Q_H}} = -351.81\ J/mol$$

Q_C: $0 = Q_C + Q_H + W_{comp}$ (Overall energy Balance)

$$0 = Q_C - 351.81\ J/mol + 28.52\ J/mol$$

$$\underline{\underline{Q_C}} = +323.29\ J/mol \quad ✓ \qquad Q_C = \Delta H_{4\to 1}$$

W_{net}: $W_{net} = W_{comp}$

$$W_{net} = +28.52\ J/mol$$

$$\omega = \frac{|Q_C|}{W_{net}} \qquad \omega = \frac{323.29\ J/mol}{28.52\ J/mol} \qquad \boxed{\omega = 11.34}$$

OK

Quizzes 1-10

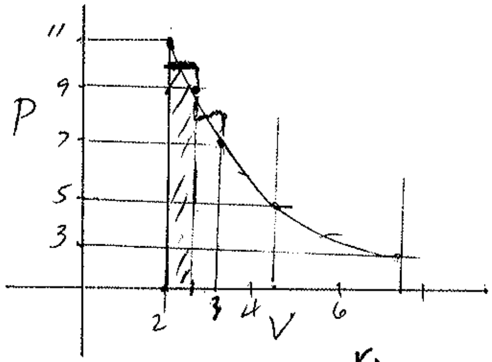
January 10, 2013

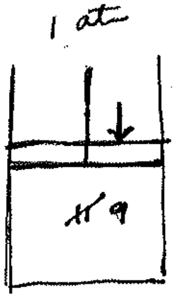
CHME 223

Quiz #1

High pressure gas expands in a cylinder by pushing back a frictionless piston, thus doing work on the atmosphere which is at 1 atm. During the expansion the following data are recorded. How much work in joules is done by this expansion?

	Volume of gas in the cylinder lit ✓	**Pressure of gas in the cylinder atm**		**Net pressure atm** ✓
at start →	2.0	12	Outside	11
	2.4	10	air	9
	3.0	8	resists	7
	4.3	6	at	5
at end →	7.6	4	1 atm	3





$$W = -\int_{V_1}^{V_2} P\, dV$$

$$W = -\left[(10)(.4) + 8(.6) + 6(1.3) + 4(3.3)\right]$$

$$W = -29.8 \text{ L}\cdot\text{atm}$$

$$W = -3020 \text{ J}$$

$$101.32 = 1 \text{ L}\cdot\text{atm}$$

January 17, 2013

CHME 223

Quiz #2

Open book – No notes

Which requires more heat input, to heat a gas in a constant pressure cylinder or in a constant volume bomb? Explain.

CLOSED SYSTEM

$$\Delta U = Q + W$$

COMP. OR EXPANSION

$$W = -\int_{V_1}^{V_2} P\,dV$$

$$\Delta U = Q \qquad \text{CONST. } V$$

$$\Delta U = Q - \int_{V_1}^{V_2} P\,dV \qquad \text{CONST. } P$$

$$Q = \Delta U + \int_{V_1}^{V_2} P\,dV$$

COMMENTS:

ΔT = CONST FOR BOTH PROCESSES

$\therefore$ ΔU = THE SAME FOR BOTH PROCESSES

MOLECULES ARE AT THE SAME ENERGY LEVEL ?

IF NO P EFFECT.

BE CAREFUL WHEN USING MODIFIERS. SO.

FOR EXAMPLE.

EASIER.

HARDER.

A LOT OF.

Zach Foster

10

January 24, 2012

CHME 223

Quiz #3

For liquid water the isothermal compressibility is given by κ = c /V(P+b); where c and b are functions of temperature only. If 1 kg of water is compressed isothermally and reversibly from 1 to 500 bar at 60 C, how much work is required? At 60 C, b = 2700 bar and c = 0.125 cm^3g^{-1}.

$$K_{H_2O} = \frac{c}{V(P+b)} = \frac{0.125\ cm^3/g}{V(P+2700\ (bar))}$$

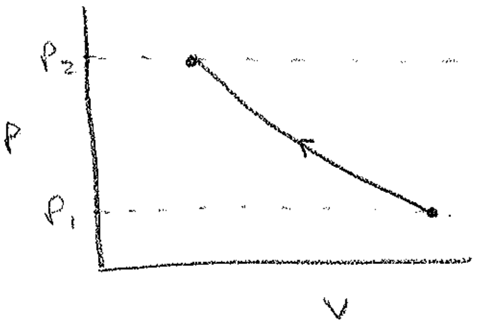
1 Kg H_2O

$P_1 = 1$ bar $P_2 = 500$ bar

T = 60°C = 333.15 K

$$\frac{0.125\ (cm^3/g)}{V(P+2700\ (bar))} = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

$$\left(\frac{\partial V}{\partial P}\right)_T = \frac{-0.125\ (cm^3/g)}{(P+2700(bar))}$$



$$dV = \left(\frac{\partial V}{\partial T}\right)_P \overset{0}{\cancel{dT}} + \left(\frac{\partial V}{\partial P}\right)_T dP$$

$$dV = \left(\frac{\partial V}{\partial P}\right)_T dP = \frac{-0.125\ (cm^3/g)}{(P+2700(bar))}\,dP$$

$$W = -\int P\,dV \qquad W = -\int_{P_1}^{P_2} P\left(\frac{-0.125\ (cm^3/g)}{(P+2700(bar))}\right)dP$$ ✓

$$W = \int_1^{500} P\left(\frac{0.125\ (cm^3/g)}{(P+2700(bar))}\right)dP \qquad W = 5.159\ (cm^3/g)\cdot bar$$

$$\frac{5.159\ (cm^3)\cdot bar}{g\ H_2O}\left|\ 1\ Kg(H_2O)\ \right|\frac{1000\ (g)}{1\ Kg} = 5159\ (cm^3\cdot bar)$$

$$5159\ (cm^3\cdot bar)\left|\frac{1\ (J)}{10\ (cm^3\cdot bar)}\right| = 515.9\ J$$

$$\boxed{W = 516\ J}$$ ✓

Zach Foster

8

January 31, 2013

CHME 223

Quiz #4

Open book – No notes

Determine a good estimate for the compressibility factor Z of a saturated hydrogen vapor at 25 K and 3.213 bar.

Hydrogen (From Table B-1 p.681)

MW = 2.016 ω = −0.216 T_c = 33.19 (K) P_c = 13.13 (bar)

Z_c = 0.305 V_c = 64.1 (cm³/mol) T_n = 20.4 (K)

T = 25 (K) P = 3.213 (bar) FIND T_r, P_r (EFFECTIVE)

$T_r = T/T_c = 25/33.19 = \underline{0.7532} = T_r$

$P_r = P/P_c = 3.213/13.13 = \underline{0.2447} = P_r$

$$Z = 1 + B^\circ \frac{P_r}{T_r} + \omega B' \frac{P_r}{T_r}$$

$B^\circ = 0.083 - \frac{0.422}{T_r^{1.6}} = 0.083 - \frac{0.422}{(0.7532)^{1.6}} = \underline{-0.5811} = B^\circ$

$B' = 0.139 - \frac{0.172}{T_r^{4.2}} = 0.139 - \frac{0.172}{(0.7532)^{4.2}} = \underline{-0.4265 = B'}$

$\frac{P_r}{T_r} = \frac{0.2447}{0.7532} = \underline{0.3249 = \frac{P_r}{T_r}}$

$Z = 1 + (-0.5811)(0.3249) - 0.216(-0.4265)(0.3249)$

$\boxed{Z = 0.841}$

February 7, 2013

CHME 223

10

Quiz #5

The following enthalpy changes are known for reactions at 25 C in the standard state.

No.			$\Delta H°$(kJ/gmol)
~~1~~	$C_3H_6(g) + H_2(g)$	$\longrightarrow C_3H_8(g)$	−123.8
~~2~~	$C_3H_8(g) + 5O_2(g)$	$\longrightarrow 3CO_2(g) + 4H_2O(l)$	−2220.0
3	$H_2(g) + \frac{1}{2}O_2(g)$	$\longrightarrow H_2O(l)$	−285.8
~~4~~	~~$H_2O(l)$~~	~~$\longrightarrow H_2O(g)$~~	~~43.9~~
~~5~~	~~$C(diamond) + O_2(g)$~~	~~$\longrightarrow CO_2(g)$~~	~~−395.4~~
6	$C(graphite) + O_2(g)$	$\longrightarrow CO_2(g)$	−393.5

Calculate the heat of formation of propylene.

	$\Delta H°$ (kJ/gmol)
$C_3H_{6(g)} + H_{2(g)} \longrightarrow \cancel{C_3H_8}_{(g)}$	−123.8
$\cancel{C_3H_8}_{(g)} + \cancel{5O_2}_{(g)} \longrightarrow 3CO_{2(g)} + \cancel{4H_2O}_{(l)}$	−2220.0
$\cancel{4H_2O}_{(l)} \longrightarrow 4H_{2(g)} + \cancel{2O_2}_{(g)}$	4(285.8)
$3CO_{2(g)} \longrightarrow 3C_{(graphite)} + \cancel{3O_2}_{(g)}$	3(393.5)
$C_3H_6 \longrightarrow 3H_2 + 3C_{(graphite)}$	−20.1
$3H_2 + 3C_{(graphite)} \longrightarrow C_3H_6$	20.1

$$\boxed{\Delta H_f^{25°C} = 20.1\ (kJ/gmol)}$$ ✓

John Burke

10

February 13, 2013

CHME 223

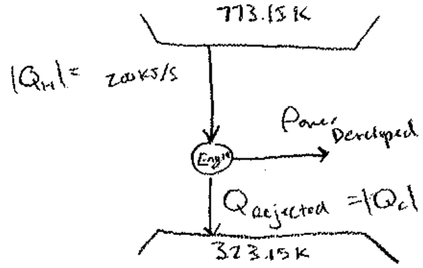
Quiz #6

A Carnot engine receives 200 kJ/s of heat from a heat source at 500 C and rejects heat to a heat sink reservoir at 50 C. What are the power developed and the heat rejected?

$T_H = 500°C = 773.15\ K$

$T_C = 50°C = 323.15\ K$

$Q_{in} = 200\ KJ/s$



1 $Q_{In} - W = Q_{rejected}$

2

$$\eta = \frac{|W|}{|Q_H|} = 1 - \frac{T_C}{T_H} = 1 - \frac{323.15K}{773.15K} = \underset{\text{efficiency}}{0.5820}$$

or could have used direct relationship $\frac{|Q_H|}{T_H} = \frac{|Q_C|}{T_C}$

$\eta = \frac{|W|}{|Q_H|}$; $0.5820 = \frac{|W|}{200 KJ/s}$ $W = 116.4\ KJ/s$

$\boxed{\text{Power developed} = 116.4\ KJ/s}$ ✓ KW

$200\ KJ/s - 116.4\ KJ/s = Q_{rejected}$

$\boxed{Q_{rejected} = 83.6\ KJ/s}$ ✓

March 7, 2013

CHME 223

Quiz #7

Show clearly that the following result is true:

$$\left(\frac{\partial U}{\partial P}\right)_T = -T\left(\frac{\partial V}{\partial T}\right)_P - P\left(\frac{\partial V}{\partial P}\right)_T$$

For the virial equation of state $PV/RT = 1 + BP$ evaluate the above partial derivative (B is a function of temperature) .

$$dU = T\,dS - P\,dV$$

$$\left(\frac{\partial U}{\partial P}\right)_T = T\left(\frac{\partial S}{\partial P}\right)_T - P\left(\frac{\partial V}{\partial P}\right)_T$$

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P$$

$$\boxed{\left(\frac{\partial U}{\partial P}\right)_T = -T\left(\frac{\partial V}{\partial T}\right)_P - P\left(\frac{\partial V}{\partial P}\right)_T}$$

$$PV = RT + RTBP \qquad V = \frac{RT}{P} + RTB$$

$$\left(\frac{\partial V}{\partial T}\right)_P = \frac{R}{P} + R\left(B'T + B\right)$$

$$\left(\frac{\partial V}{\partial P}\right)_T = \frac{-RT}{P^2}$$

$$\left(\frac{\partial U}{\partial P}\right)_T = -T\left(\frac{R}{P} + R(B'T+B)\right) + \frac{RT}{P}$$

$$\boxed{\left(\frac{\partial U}{\partial P}\right)_T = -RT\left(B'T+B\right)}$$

March 14, 2013

CHME 223

Quiz #8

Four kg of steam in a piston/cylinder device is at 800 kPa and 200 C. If it undergoes a reversible, adiabatic expansion to 150 kPa, what is its final temperature and how much work is done?

$P_1 = 800$ kpa

$T_1 = 200$C

$H_1 = 2838.6$ kJ/kg

$S_1 = 6.8148$ kJ/kg/K

$U_1 = 2629.9$ kJ/kg

$P_2 = 150$ kpa

$S_2 = S_1 = 6.8148$

$\boxed{T_2 = 111.37°C = 384.52\,K}$

$S_2 = x_\ell s_\ell + x_v s_v$

$6.8148 = (1-x_v)(1.4336) + x_v(7.2234)$

$x_v = .93$

$W + Q = \Delta U$

$U_2 = (.07)(466.968) + (.93)(2519.5)$

$u_2 = 2375.8$ kJ/kg

$Q = 0$

$W = m\Delta U$

$= 4(2375.8 - 2629.9)$

$\boxed{W = -1014.3\ kJ}$

March 28, 2013

CHME 223

Quiz #9

Carbon dioxide expands at constant enthalpy (as in a throttling process) from 240 psia and 100 F to 30 psia. Estimate ΔS in J mol^{-1} K^{-1} for the process from the attached pressure-enthalpy chart.

$$S_1 = .375 \text{ BTU/lbm/°R}$$

$$S_2 = .470 \quad "$$

$$\Delta S = S_2 - S_1 = .095 \text{ BTU/lbm/°R}$$

$$\Delta S = .095 \frac{\text{BTU}}{\text{lbm °R}} \times \frac{1.8 \text{ °R}}{\text{°K}} \times \frac{\text{lbm}}{454 \text{ g}} \times \frac{44 \text{ g}}{\text{g mol}} \times \frac{\text{J}}{9.478 \times 10^{-4}}$$

$$\Delta S = 17.49 \text{ J/mol/K}$$

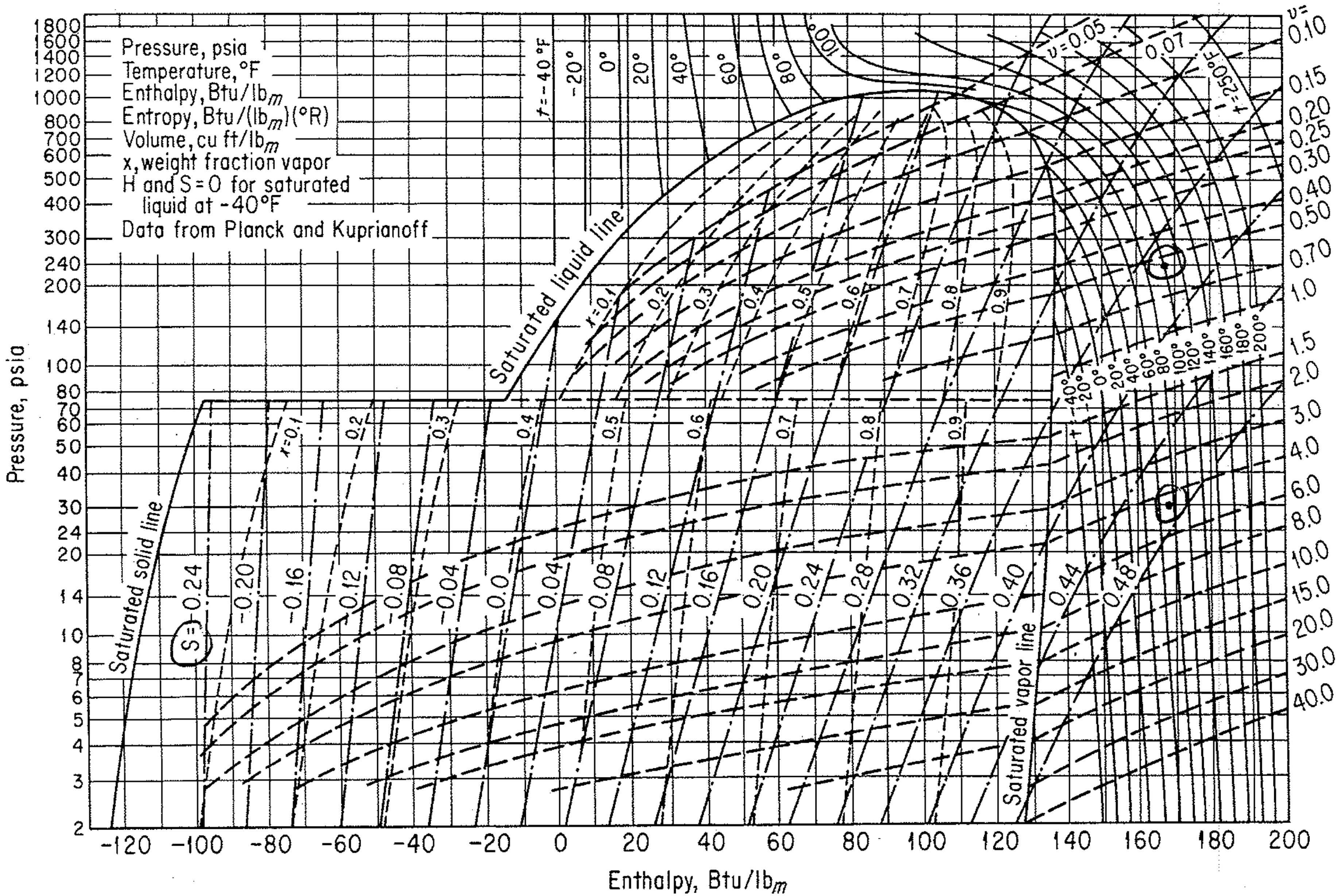


Figure J.2 Pressure-enthalpy chart for carbon dioxide.

April 18, 2013

CHME 223

Quiz #10

A two stage Carnot refrigeration system (Fig. 9.3) operates between $T_C = -60$ F and $T_H = 80$ F. Intermediate temperature are $T'_C = 0$ F and $T'_H = 10$ F. The refrigerant is tetrafluoroethane. Trace the path of the process on the PH diagram below.

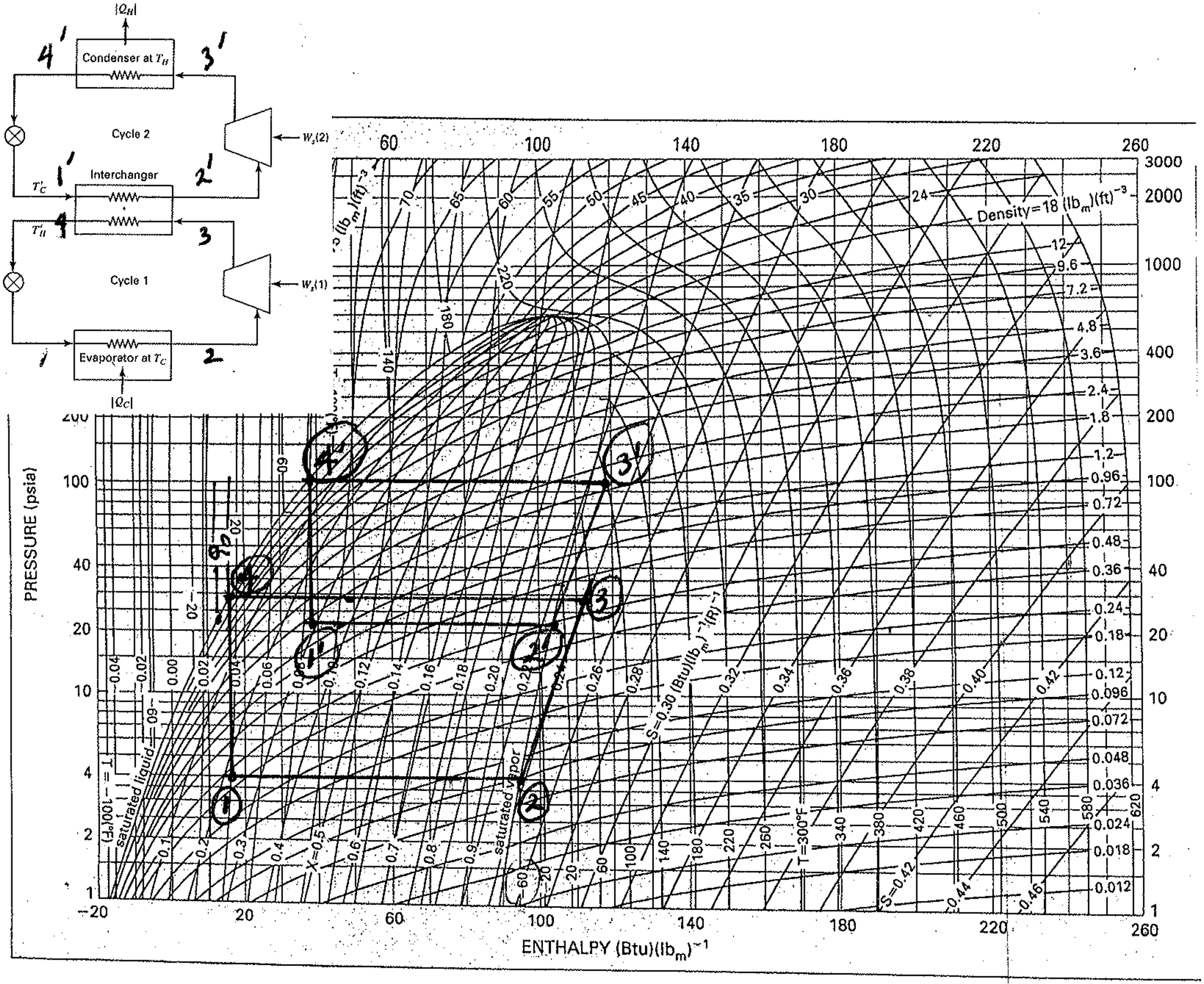


Figure G.2: *PH* diagram for tetrafluoroethane (HFC-134a). (*Reproduced by permission. ASHRAE Handbook: Fundamentals*, p. 17.28, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 1993.)

Representative
Homework Assignments

Homework #3

Problem statements.

3.33. Calculate Z and V for ethane at 50°C and 15 bar by the following equations:

(*a*) The truncated virial equation [Eq. (3.40)] with the following experimental values of virial coefficients:

$$B = -156.7 \text{ cm}^3 \text{ mol}^{-1} \qquad C = 9{,}650 \text{ cm}^6 \text{ mol}^{-2}$$

(*b*) The truncated virial equation [Eq. (3.38)], with a value of B from the generalized Pitzer correlation [Eq. (3.63)].

(*c*) The Redlich/Kwong equation.

(*d*) The Soave/Redlich/Kwong equation.

(*e*) The Peng/Robinson equation.

3.35. Determine Z and V for steam at 250°C and 1,800 kPa by the following:

(*a*) The truncated virial equation [Eq. (3.40)] with the following experimental values of virial coefficients:

$$B = -152.5 \text{ cm}^3 \text{ mol}^{-1} \qquad C = -5{,}800 \text{ cm}^6 \text{ mol}^{-2}$$

(*b*) The truncated virial equation [Eq. (3.38)], with a value of B from the generalized Pitzer correlation [Eq. (3.63)].

(*c*) The steam tables (App. F).

3.36. With respect to the virial expansions, Eqs. (3.11) and (3.12), show that:

$$B' = \left(\frac{\partial Z}{\partial P}\right)_{T,P=0} \qquad \text{and} \qquad B = \left(\frac{\partial Z}{\partial \rho}\right)_{T,\rho=0}$$

where $\rho \equiv 1/V$.

3.45. A 30-m^3 tank contains 14 m^3 of liquid n-butane in equilibrium with its vapor at 25°C. Estimate the mass of n-butane vapor in the tank. The vapor pressure of n-butane at the given temperature is 2.43 bar.

3.51. A rigid vessel, filled to one-half its volume with liquid nitrogen at its normal boiling point, is allowed to warm to 25°C. What pressure is developed? The molar volume of liquid nitrogen at its normal boiling point is 34.7 cm^3 mol^{-1}.

3.57. For a gas described by the Redlich/Kwong equation and for a temperature greater than T_c, develop expressions for the two limiting slopes,

$$\lim_{P\to 0}\left(\frac{\partial Z}{\partial P}\right)_T \qquad \lim_{P\to\infty}\left(\frac{\partial Z}{\partial P}\right)_T \qquad \left(\frac{\partial Z}{\partial V}\right)_T \Big/ \left(\frac{\partial P}{\partial V}\right)_T$$

Note that in the limit as $P \to 0$, $V \to \infty$, and that in the limit as $P \to \infty$, $V \to b$.

3.73. Storage is required for 35,000 kg of propane, received as a gas at 10°C and 1(atm). Two proposals have been made:

(*a*) Store it as a gas at 10°C and 1(atm).

(*b*) Store it as a liquid in equilibrium with its vapor at 10°C and 6.294(atm). For this mode of storage, 90% of the tank volume is occupied by liquid.

31 January 2013 | CHME 223 Noureddini SEC 001 S2013 | Zach Foster

Ch 3 # 33, 35, 36, 45, 51, 57, 73

HW #3

$\frac{66}{70}$

3.33) Calculate Z and V for ethane at 50°C and 15 bar by the following equations:

a) Truncated virial Equation

$B = -156.7\ (cm^3/mol) \qquad C = 9650\ (cm^6/mol)$

$Z = \frac{PV}{RT} = 1 + \frac{B}{V} + \frac{C}{V^2} \qquad V_{i+1} = \frac{RT}{P}\left(1 + \frac{B}{V_i} + \frac{C}{V_i^2}\right)$

Using wolfram alpha $\boxed{V = 1630\ (cm^3/mol)}$ ✓ $\boxed{Z = 0.907}$

b) Truncated virial Equation

$\hat{B} = B^0 + \omega B^1 \qquad B^0 = 0.083 - \frac{0.422}{T_r^{1.6}} \qquad B^1 = 0.139 - \frac{0.172}{T_r^{4.2}}$

$\underline{T_c = 305.3 (K)} \qquad \underline{B^0 = -0.3023} \qquad \underline{B^1 = 0.003517}$

$T_r = T/T_c = \underline{1.0584 = T_r}$

$\underline{\omega = 0.100} \qquad \hat{B} = (-0.3023) + 0.100(0.003517)$

$\underline{\hat{B} = -0.3019\ (cm^3/mol)}$ X(-1)

$Z = \frac{PV}{RT} = 1 + \frac{\hat{B}P}{RT} \qquad V = \frac{RT}{P} + \hat{B} \qquad \boxed{V = 1790\ (cm^3/mol)} \ \boxed{Z = 0.9998}$

c) Redlich/Kwong $\qquad \underline{P_c = 48.72 (bar)}$

$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)} \qquad a(T) = \frac{\Psi \alpha(T_r) R^2 T_c^2}{P_c} \qquad b = \Omega \frac{RT_c}{P_c}$

$a(T) = \frac{(0.42748)(1.0584)^{-1/2} R^2 (305.3(K))^2}{48.72} \qquad \underline{a(T) = 5495478.715}$

$b = \frac{0.08664 (R)(305.3(K))}{48.72} \qquad \underline{b = 45.141}$

$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)} = \frac{R(323.15(K))}{V - 45.141} - \frac{5495478.715}{V(V + 45.141)} = 15 (bar)$

$\boxed{V = 1620\ (cm^3/mol)} \qquad Z = \frac{PV}{RT} \qquad \boxed{Z = 0.906}$

d) Soave/Redlich/Kwong

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)} \qquad a(T) = \frac{\Psi \alpha(T_r) R^2 T_c^2}{P_c} = \underline{5448438.438 = a}$$

$$b = \Omega \frac{RT_c}{P_c} = \underline{45.141 = b}$$

$$\alpha = (1 + (0.480 + (1.574 \cdot \omega) - (0.176 \cdot \omega^2))(1 - T_r^{0.5}))^2$$

$$\alpha = 0.9636994308$$

$$P = 15(\text{bar}) = \frac{R(323.15\ (K))}{V - 45.141} - \frac{(0.963463)(5647321.595)}{V(V + 45.141)}$$

$\boxed{V = 1630\ (cm^3/mol)}$ ✓ $Z = \frac{PV}{RT}$ $\boxed{Z = 0.907}$

e) Peng-Robinson

$$a(T) = \frac{\Psi \alpha(T_r) R^2 T_c^2}{P_c} = 5865261.391$$

$$P = \frac{RT}{V-b} - \frac{a(T)}{(V + (1-\sqrt{2})b)(V + (1+\sqrt{2})b)} \qquad b = \Omega \frac{RT_c}{P_c} = 40.53528956$$

$$\alpha(T_r) = \left[1 + (0.37464 + 1.54226\omega - 0.26992\omega^2)(1 - T_r^{1/2})\right]^2$$

$$\alpha(T_r) = 0.9699034645$$

$\boxed{V = 1610\ (cm^3/mol)}$ $Z = \frac{PV}{RT}$ $\boxed{Z = 0.896}$

3.35) Determine V & Z for steam at 250°C & 1800 kPa (523.15, 18 bar)

a) Truncated virial Equation

$B = -152.5 (cm^3/mol)$ $\quad C = -5800 (cm^6/mol)$

$Z = \frac{PV}{RT} = 1 + \frac{B}{V} + \frac{C}{V^2}$ $\quad V = \frac{RT}{P}\left(1 + \frac{B}{V} + \frac{C}{V^2}\right)$

$\boxed{V = 2250 \ (cm^3/mol)}$ $\quad \boxed{Z = 0.931}$

b.) Truncated virial

$\hat{B} = B^0 + \omega B^1$ $\quad T_r = T/T_c = 523.15(K)/647.1(K) = 0.808415$

$B^0 = 0.083 - \frac{0.422}{T_r^{1.6}} = -0.51001$

$B^1 = 0.139 - \frac{0.172}{T_r^{4.2}} = -0.28112$

$\omega = 0.345$ $\quad \hat{B} = -0.6070$

$Z = \frac{PV}{RT} = 1 + \frac{\hat{B}P}{RT}$ $\quad V = \frac{RT}{P} + \hat{B}$

$\boxed{V = 2420 \ (cm^3/mol)}$ $\quad \boxed{Z = 0.9997}$

c.) Steam Tables

$V = 124.99 \ (cm^3/g) \,\Big|\, \frac{18\ (g)}{mol}$ $\quad \boxed{V = 2250 \ cm^3/mol}$

$Z = PV/RT$ $\quad \boxed{Z = 0.931}$

3.36) With respect to virial expansions, show that

$$B' = \left(\frac{\partial Z}{\partial P}\right)_{T,P=0} \quad \text{and} \quad B = \left(\frac{\partial Z}{\partial \rho}\right)_{T,\rho=0}$$

where $\rho = 1/V$.

(3.11) $Z = 1 + B'P = \frac{PV}{RT}$

(3.12) $Z = 1 + \frac{B}{V} = \frac{PV}{RT}$

$$\left(\frac{\partial}{\partial P}\right)_T \left(Z = 1 + B'P + C'P^2 + D'P^3 + \dots\right)$$

$$\left(\frac{\partial Z}{\partial P}\right)_T = B' + 2PC' + 3P^2D' + \dots$$

At $P = 0$, $\cancelto{0}{2PC'}$ $\cancelto{0}{3P^2D'}$ etc...

$$\left(\frac{\partial Z}{\partial P}\right)_{T,P=0} = B'$$ ✓

$$\left(Z = 1 + \frac{B}{V} + \frac{C}{V^2} + \frac{D}{V^3} + \dots\right)$$

$\rho = 1/V$

$$\left(\frac{\partial}{\partial \rho}\right)_T \left(Z = 1 + B\rho + C\rho^2 + D\rho^3 + \dots\right)$$

$$\left(\frac{\partial Z}{\partial \rho}\right)_T = B + 2\rho C + 3\rho^2 D + \dots$$

At $\rho = 0$, $\cancelto{0}{2\rho C}$ $\cancelto{0}{3\rho^2 D}$ etc...

$$\left(\frac{\partial Z}{\partial \rho}\right)_{T,\rho=0} = B$$

3.45) A 30 m^3 tank contains 14 m^3 of liquid n-butane in equilibrium with its vapor at 25°C. Estimate mass of n-butane vapor in tank. $P_{vapor} = 2.43$ bar

Redich-Kwong:

$$P = \frac{RT}{V-b} - \frac{a}{\sqrt{T}\,V(V+b)} \qquad a = \frac{0.4275\, R^2 T_c^{5/2}}{P_c} \qquad b = \frac{0.08664\, R T_c}{P_c}$$

$T_c = 425.1$ K

$P_c = 37.96$ bar

$a = 290072123.1 \qquad b = 80.67$

$$2.43\ (\text{bar}) = \frac{R(298.15\ \text{K})}{V-80.67} - \frac{290072123.1}{\sqrt{298.15}\,V(V+80.67)}$$

$$\hat{V}_{gas} = 8070.07\ (\text{cm}^3/\text{mol})$$

$$V_{gas} = 30 - 14\ (\text{m}^3) = 16\ (\text{m}^3)$$

$$\frac{16\ (\text{m}^3)}{} \Big| \frac{(\text{mol})}{8070.07\ (\text{cm}^3)} \Big| \frac{10^6\ (\text{cm}^3)}{1\ (\text{m}^3)} = 1982.63\ (\text{mol})$$

$$\frac{1982.63\ (\text{mol})}{} \Big| \frac{58.123\ (\text{g})}{(\text{mol})} \Big| \frac{1\ (\text{kg})}{1000\ (\text{g})} = \boxed{115\ \text{Kg}}$$

X(-1)

3.51.) Rigid vessel filled to 1/2 volume with liquid nitrogen at normal boiling point.
Warms to 25°C. What pressure developed?
$V = 34.7\ (cm^3/mol)$ at boiling point

$T = 25°C = 298.15\ (K)$

$T_c(N_2) = 126.2\ (K)$, so N_2 is in the fluid state

Assume a basis of 1 mole liquid N_2 to begin:

$V_\ell = 34.7\ cm^3$
$V_{T,0} = 69.4\ cm^3$

During initial state:
$P = 1\ (atm) = 1.01325\ (bar)$
$T_n(N_2) = 77.3\ (K)$

$T_c = 126.2\ (K)$ $P_c = 34\ (bar)$ $V_c = 89.2\ (cm^3/mol)$ $\omega = 0.038$

$T_r = T/T_c = 0.613$
$P_r = P/P_c = 0.03$

$Z = Z^\circ + \omega Z'$

$$Z^\circ = 1 + B^\circ \frac{P_r}{T_r}$$

$B^\circ = 0.083 - \frac{0.422}{T_r^{1.6}} = -0.841528$ $Z^\circ = 1 + B^\circ \frac{P_r}{T_r} = 0.95878$

$B' = 0.139 - \frac{0.172}{T_r^{4.2}} = -1.208795$ $Z' = B' \frac{P_r}{T_r} = -0.0592$

$Z = 0.95878 + (0.038)(-0.0592) = 0.957$

$PV = nRT$ $Z = \frac{PV}{nRT}$ $n = \frac{PV}{RTZ}$ $n = 0.00572$ (moles gas initial)

$\hat{V}_{gf} = \frac{69.4\ (cm^3)}{(1 + 0.005716)}$ $\hat{J} = 69.0055\ (cm^3/mol)$

$P = \frac{RT}{V-b} - \frac{a(T)}{V^2}$ $a(T) = \frac{\psi\, \alpha(T_r) R^2 T_c^2}{P_c^2}$ $b = \frac{\Omega R T_c}{P_c}$

$a(T) = 40180.28213$ $b = 38.5767$

$$P = \frac{R(298.15(K))}{(69.0055\ (cm^3/mol) - 38.5767\ (cm^3/mol))} - \frac{40180.28213\ (cm^6/mol^2)(bar)}{(69.0055\ (cm^3/mol)^2)}$$

$P = 806$ bar $\boxed{P = 810\ \text{bar}}$ X(-1)

3.57) For a gas described by Redlich-Kwong and $T > T_c$, develop expressions for:

$$\lim_{P \to 0} \left(\frac{\partial Z}{\partial P}\right)_T \qquad \lim_{P \to \infty} \left(\frac{\partial Z}{\partial P}\right)_T$$

$(P \to 0,\ V \to \infty)$ $\qquad$ $(P \to \infty,\ V \to b)$

RK:
Solved for compressibility factor (from wikipedia)

$$Z = \frac{PV_m}{RT} = \frac{1}{1-h} - \frac{A^2}{B}\frac{h}{1+h}$$

$$Z = \frac{1}{\left(1 - \frac{b}{V_m}\right)} - \left(\frac{0.4278 T_c^{2.5}}{P_c\ T^{2.5}}\right)\left(\frac{P_c T}{0.0867 T_c}\right)\frac{\left(\frac{b}{V_m}\right)}{\left(1 + \frac{b}{V_m}\right)}$$

where: $b = \frac{0.08664 R T_c}{P_c}$

$$\left(\frac{\partial}{\partial V}\right)_T \left(Z = \frac{1}{\left(1 - \frac{b}{V}\right)} - \frac{0.4278 T_c^{1.5}}{(0.0867) T^{1.5}}\left(\frac{\frac{b}{V}}{1 + \frac{b}{V}}\right)\right)$$

$$\left(\frac{\partial Z}{\partial V}\right)_T = \frac{b \ln(V)}{\left(1 - \frac{b}{V}\right)^2} - \frac{0.4278 T_c^{1.5}\, b}{(0.0867) T^{1.5} (V+b)^2}$$

RK:
Solved for pressure $\qquad a = \frac{0.4275 R^2 T_c^{5/2}}{P_c}$

$$\left(\frac{\partial}{\partial V}\right)_T \left(P = \frac{RT}{V-b} - \frac{a(T)}{(V(V+b))} = \frac{RT}{V-b} - \frac{a}{\sqrt{T}(V(V+b))} \right)$$

$$\left(\frac{\partial P}{\partial V}\right)_T = \frac{-RT}{(V-b)^2} + \frac{a(2V+b)}{(T^{1/2})(V^2)(V+b)^2}$$

$$\left(\frac{\partial Z}{\partial P}\right)_T = \left(\frac{\partial Z}{\partial V}\right)_T \Big/ \left(\frac{\partial P}{\partial V}\right)_T$$

$$\left(\frac{\partial Z}{\partial P}\right)_T = \frac{\left(\frac{b \ln(V)}{\left(1 - \frac{b}{V}\right)^2} - \frac{4.9342(b)}{T_r^{3/2}(V+b)^2}\right)}{\frac{-RT}{(V-b)^2} + \frac{a(2V+b)}{(T^{1/2})(V^2)(V+b)^2}} = \frac{aV^2(V-b)^2 - bRT^{3/2}V^2(V+b)^2}{aRT(2V+b)(V-b)^2 - R^2T^{5/2}V^2(V+b)^2}$$

$$\boxed{\lim_{\substack{P \to 0 \\ (v \to \infty)}} \left(\frac{\partial z}{\partial P}\right)_T = \frac{b - \frac{a}{RT^{3/2}}}{RT}}$$

$$\lim_{\substack{P \to \infty \\ (v \to b)}} \left(\frac{\partial z}{\partial P}\right)_T = \frac{\cancel{4b^{5}}RT^{3/2}}{R^2T^{5/2}\cancel{4b^4}} = \boxed{\lim_{\substack{P \to \infty \\ (v \to b)}} \left(\frac{\partial z}{\partial P}\right)_T = \frac{b}{RT}}$$

3.73) 35000 kg propane gas at
$T = 10°C = 283.15 (K)$ $P = 1\ atm = 1.01325\ (bar)$

Propane:

$MW = 44.097$ $\omega = 0.152$ $T_c = 369.8\ K$ $P_c = 42.48\ bar$
$Z_c = 0.276$ $V_c = 200.0\ cm^3/mol$ $T_n = 231.1\ K$

(a) Store as a gas

$$P = \frac{RT}{V-b} - \frac{a(T)}{V^2} \qquad a(T) = \frac{\Psi \alpha(T_r) R^2 T_c^2}{P_c} \qquad b = \Omega \frac{R T_c}{P_c}$$

$$a(T) = 9388612.438 \qquad b = 90.47$$

$$1.01325 = \frac{R(283.15 (K))}{(V - 90.47)} - \frac{9388612.438}{V^2}$$

$V = 138.406\ cm^3/mol$

$$\frac{35000 (kg)}{} \left| \frac{1000 (g)}{(kg)} \right| \frac{(mol)}{44.097 (g)} \left| \frac{138.406 (cm^3)}{mol} \right| \frac{(m^3)}{10^6 (cm^3)}$$

$V = 109.85$ $\boxed{V = 110 (m^3) \text{ needed for storage}}$

X(-1)

(b) Liquid (90% tank volume) in equilibrium with vapor at 10°C and 6.294 atm

$T = 283.15 (K)$ $P = 6.3773955 (bar)$

$T_r = T/T_c = 0.76568$ $P_r = P/P_c = 0.150127$

$$V_{sat} = V_c Z_c^{(1-T_r)^{2/7}} \qquad V_{sat} = 85.45 (cm^3/mol)$$

$$\frac{35000 (kg)}{} \left| \frac{1000 (g)}{(kg)} \right| \frac{(mol)}{44.097 (g)} \left| \frac{85.45 (cm^3)}{(mol)} \right| \frac{(m^3)}{10^6 (cm^3)}$$

$V_L = 67.822 = 0.9\ V_{total}$ $V = 75.4 = 75 (m^3)$

$\boxed{V = 75 (m^3) \text{ needed for storage}}$

The liquid-vapor storage occupies less space, but would require an extra process (and energy) as well as a more rigid container to be pressurized to 6.294 atm.

3.33, 36, 45, 51, 57, 35

Katie Coleman

69/70

$\boxed{3.33}$

T = 50°C = 323K   Z & V for...

P = 15 bar

ethane

a) $B = -156.7\ cm^3/mol \quad C = 9650\ cm^6/mol^2$

$Z = \frac{PV}{RT} = 1 + \frac{B}{V} + \frac{C}{V^2}$

$\frac{PV^2}{RT} = V^2 + BV + C$

$\boxed{V = 1625\ cm^3/mol}$

$Z = \frac{PV}{RT} = \frac{15 \cdot 1625}{83.14 \cdot 323}$

$\boxed{Z = 0.908}$

b) $Z = \frac{PV}{RT} = 1 + \frac{BP}{RT}$

$T_r = T/T_c$

$T_r = 323/305.3 = 1.06$

$B = -0.301 + 0.1 \cdot 0.004$

$B = -0.301$

$\boxed{V = 1634\ cm^3/mol}$

$B = B^0 + \omega B' \quad \omega = 0.100$

$B^0 = 0.083 - \frac{0.422}{T_r^{1.6}} = -0.303$

$B' = 0.139 - \frac{0.172}{T_r^{4.2}} = 3.157 \times 10^{-3}$

$Z = 1 + -.303 + 0.1 \cdot 3.157 \times 10^{-3} \frac{P_r}{T_r} = \boxed{0.912}$

c) $P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)}$

$\alpha(T_r) = T_r^{-1/2}$

$\Psi = 0.42748$

$\Omega = 0.08664$

$T_c = 305.3K$

$P_c = 48.72 bar$

$a(T) = \Psi \frac{\alpha(T_r) R^2 T_c^2}{P_c} \quad b = \Omega \frac{RT_c}{P_c}$

$a(T) = 0.08664 \cdot (1.06)^{-1/2} \cdot \frac{(83.14)^2 (305.3)^2}{(48.72)}$

$a(T) = 1.113 \times 10^6$

$b = 0.08664 \frac{83.14 \cdot 305.3}{48.72} = 45.139$

$P = \frac{RT}{V - 45.139} - \frac{1.113 \times 10^6}{V(V - 45.139)}$

$\boxed{V = 1622.7\ cm^3/mol}$

$Z = \frac{PV}{RT} = \boxed{0.906}$

d) $\sigma = 1 \quad \varepsilon = 0 \quad \Omega = 0.08664 \quad \Psi = 0.42748$

$\alpha = \left[1 + (0.480 + 1.574 \cdot 0.1 - 0.176(0.1)^2)(1 - T_r^{1/2})\right]^2 = 0.963$

$q = \frac{\Psi \alpha}{\Omega T_r} = \frac{0.42748 \cdot 0.963}{0.08664 \cdot 1.06} = 4.48 \quad \beta = \Omega \frac{P_r}{T_r} = 0.025$

$Z = 1 + 0.025 - 4.48 \cdot 0.025 \cdot \left(\frac{Z - 0.025}{(Z)(Z + 0.025)}\right)$

$\boxed{Z = 0.907}$

$V = \frac{ZRT}{P} = \boxed{1624.8\ cm^3/mol}$

$\boxed{3.33}$ e) $\sigma = 1+\sqrt{2}$ $\varepsilon = 1-\sqrt{2}$ $\Omega = 0.07779$ $\Psi = 0.45724$

$$\alpha = \left[1 + (0.37464 + 1.54226 \cdot 0.1 - 0.26992(0.1)^2)(1 - T_r^{1/2})\right]^2 = 1.301$$

$$q = \frac{\Psi \alpha}{\Omega T_r} = 7.214 \qquad \beta = \Omega \frac{P_r}{T_r} = 0.023$$

$$Z = 0.023 + (Z + (1-\sqrt{2})0.023)(Z + (1+\sqrt{2})0.023)\left(\frac{1 + 0.023 - Z}{7.214 \cdot 0.023}\right)$$

$\boxed{Z = 0.896}$ $V = \frac{ZRT}{P} = \boxed{1605.5\ \mathrm{cm^3/mol}}$

$\boxed{3.35}$

$T = 250°C$

$P = 1800\ \mathrm{kPa}$

a) $B = -152.5\ \mathrm{cm^3/mol}$ $C = -5800\ \mathrm{cm^6/mol^2}$

$$\frac{PV}{RT} = 1 + \frac{B}{V} + \frac{C}{V^2}$$

$$\frac{1800 \cdot 10^3 \cdot V}{8.314 \frac{\mathrm{m^3 Pa}}{\mathrm{mol\,K}} \cdot 523\mathrm{K}} = 1 + \frac{-152.5}{V} + \frac{-5800}{V^2}$$

$\boxed{V = 2250\ \mathrm{cm^3/mol}}$ $Z = \frac{PV}{RT} = \boxed{0.931}$

b) $T_c = 647.1\mathrm{K}$ $P_c = 220.55\ \mathrm{bar}$ $\omega = 0.345$

$T_r = T/T_c$ $P_r = P/P_c$ $B^0 = 0.083 - \frac{0.422}{T_r^{1.6}} = -0.51$

$T_r = 0.808$ $P_r = 0.082$

$B' = 0.139 - \frac{0.172}{T_r^{4.2}} = -.282$ $Z = 1 - 0.51 + 0.1(-.282) \cdot \frac{0.082}{0.808}$

$V = \frac{ZRT}{P} = \boxed{2268\ \mathrm{cm^3/mol}}$ $\boxed{Z = 0.939}$

c) $\hat{V} = 124.99 \frac{\mathrm{cm^3}}{\mathrm{g}} \cdot \frac{18\mathrm{g}}{\mathrm{mol}} = \boxed{2252\ \mathrm{cm^3/mol}}$ $MW = 18\ \mathrm{g/mol}$

$\boxed{3.36}$ $$\left(\frac{\partial Z}{\partial P}\right)_T = B' + 2C'P + 3D'P^2 + \ldots = B' + 2C'0 + 3D'0^2$$

$$\boxed{\left(\frac{\partial Z}{\partial P}\right)_{T,P=0} = B'}$$

Now $\rho = 1/V$

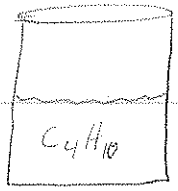
$$Z = 1 + B\rho + C\rho^2 + D\rho^3 + \ldots$$

$$\left(\frac{\partial Z}{\partial \rho}\right)_T = B + 2C\rho + 3D\rho^2 + \ldots$$

$$\boxed{\left(\frac{\partial Z}{\partial \rho}\right)_{T,\rho=0} = B}$$

$\boxed{3.45}$ n-butane

$V_{tank} = 30 m^3$
$V_e = 14 m^3$
$V_g = 16 m^3$
$T = 298K$
$V_p = 2.43$ bar



$T_c = 425.1$ K
$P_c = 37.96$ bar
$\omega = 0.200$
MW = 58.123 g/mol

$Tr = T/T_c = 0.701$
$Pr = P/P_c = 0.064$

$$B^0 = 0.083 - \frac{0.422}{(0.701)^{1.6}} = -0.662$$

$$B' = 0.139 - \frac{0.172}{(0.701)^{4.2}} = -0.626$$

$$Z = 1 + (-0.662 + 0.2 \cdot -0.626)\frac{Pr}{Tr}$$

$Z = 0.928$

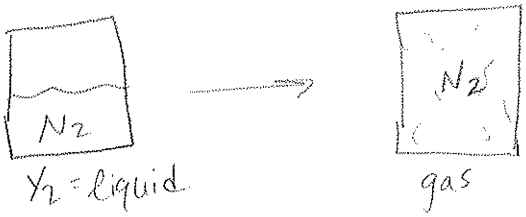
$$V = \frac{\overset{Z}{0.928} \cdot \overset{R}{83.14} \cdot \overset{T}{298}}{\underset{P}{2.43}} = 9462 \text{ cm}^3/\text{mol}$$

$$m = \frac{16m^3}{} \Big| \frac{10^6 cm^3}{1m^3} \Big| \frac{1 mol}{9462 cm^3} \Big| \frac{58.123 g}{1 mol}$$

$\boxed{m = 98.28 \text{ kg}}$

$\boxed{3.51}$

$T_i = 77.3K$
$P_i = 1$ ~~atm~~ bar
$\omega = 0.038$
$T_c = 126.2K$
$P_c = 34$ bar
MW = 28 g/mol
$V_l = 34.7 cm^3$
$V_c = 69.4 cm^3$
$P_f = ?$
$T_f = 298K$



<u>Basis</u>
1 mole
liquid

$$B_0 = 0.083 - \frac{0.422}{Tr^{1.6}}$$
$$= -0.840$$
$$B_1 = 0.139 - \frac{0.172}{Tr^{4.2}}$$
$$= -1.204$$

$T_r = T/T_c = 0.613$
$P_r = P/P_c = 0.029$

$$Z = 1 + (B_0 + \omega B_1)\frac{Pr}{Tr} = 0.958$$

$$n_v = \frac{PV_l}{ZRT} = \frac{1 bar \cdot 34.7 cm^3}{0.958 \cdot 83.4 \frac{cm^3 bar}{mol K} 77.3K} = 0.00563$$

$n_{tot} = 1 + 0.00563 = 1.00563$

$$\bar{V} = \frac{2V_e}{n_{tot}} = 69.011 \text{ cm}^3/\text{mol}$$

$T_f = 298$ K so $T/T_c = T_r = 2.361$

$\Omega = 0.08664$ $\Psi = 0.42748$ $\alpha = Tr^{1/2} = 1.537$

$$a = \frac{\Psi \alpha R^2 T_c^2}{P_c} = 0.901 \, m^3 \frac{bar\, cm^3}{mol^2}$$

$$b = \frac{\Omega R T_c}{P_c} = 26.737 \frac{cm^3}{mol}$$

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)} = \boxed{450.1 \text{ bar}}$$

$\boxed{3.57}$

$$Z = \frac{V}{V-b} - \frac{a}{RT^{3/2}(V+b)} \qquad P = \frac{RT}{V-b} - \frac{a}{T^{1/2}V(V+b)}$$

$$\left(\frac{\partial Z}{\partial V}\right)_T = \frac{a(V-b)^2 - bRT^{3/2}(V+b)^2}{RT^{3/2}(V-b)^2(V+b)^2} \qquad \left(\frac{\partial P}{\partial V}\right)_T = \frac{a(2V+b)(V-b)^2 - RT^{3/2}V^2(V+b)^2}{T^{1/2}V^2(V-b)^2(V+b)^2}$$

$$\left(\frac{\partial Z}{\partial P}\right)_T = \frac{(\partial Z/\partial V)_T}{(\partial P/\partial V)_T}$$

$$\left(\frac{\partial Z}{\partial P}\right)_T = \frac{aV^2(V-b)^2 - bRT^2V^2(V+b)^2}{aRT(2V+b)(V-b)^2 - R^2T^{3/2}V^2(V+b)^2}$$

$P \to 0,\ V \to \infty$

$$\lim_{P\to 0}\left(\frac{\partial Z}{\partial P}\right)_T = \frac{b - a/RT^{3/2}}{RT}$$ ✓

$P \to \infty\ \ V \to b$

$$\lim_{P\to\infty}\left(\frac{\partial Z}{\partial P}\right)_T = \frac{b}{RT}$$

$\boxed{3.73}$ C_3H_8 a) gas @ 283K 1atm

$m = 35{,}000\,kg$

$T = 283K$

$P = 1\,atm$

$\omega = 0.152$

$mw = 44.1$

$T_c = 369.8K$ $\qquad T_r = T/T_c = 0.765$

$P_c = 42.48\,bar$ $\qquad P_r = P/P_c = 0.024$

$B^0 = 0.083 - \frac{0.422}{T^{1.6}}$ $\qquad B^1 = 0.139 - \frac{0.172}{T_r^{4.2}}$

$B^0 = -0.565$ $\qquad B^1 = -0.391$

$Z = 1 + (-0.565 - 0.152 \cdot 0.391)\frac{0.024}{0.765} = 0.980$ ✗(-1)

$V = \frac{ZRTn}{P} = 1.81\times10^{10}\,cm^3 = \boxed{1.81\times10^4\,m^3 \text{ large tank}}$

b) $V_l = 0.9V_t$ $\qquad V_c = 200\,cm^3/mol$ $\quad Z_c = 0.276$

$V_g = 0.1V_t$

$V_l = V_c \cdot Z_c^{(1-T_r)^{0.2857}}$ $\qquad V_l = 85.444\,cm^3/mol$

$P = 6.294\,atm$

$P_r = P/P_c = 0.15$ $\qquad Z = 1 + (-0.565 - 0.152\cdot 0.391)\frac{0.15}{0.765}$

$Z = 0.878$

$V_{vap} = 3.24\times10^3\,cm^3/mol$ ✓

$V_t = \frac{V_l n}{0.9} = $ 75.133 m³ smaller tank

but is kept under pressure and refrigeration

Homework #6

Problem statements.

4.7. Calculate the heat capacity of a gas sample from the following information: The sample comes to equilibrium in a flask at 25°C and 121.3 kPa. A stopcock is opened briefly, allowing the pressure to drop to 101.3 kPa. With the stopcock closed, the flask warms, returning to 25°C, and the pressure is measured as 104.0 kPa. Determine C_P in J mol^{-1} K^{-1} assuming the gas to be ideal and the expansion of the gas remaining in the flask to be reversible and adiabatic.

4.10. Table 9.1 lists the thermodynamic properties of saturated liquid and vapor tetrafluoroethane. Making use of the vapor pressures as a function of temperature and of the saturated-liquid and saturated-vapor volumes, calculate the latent heat of vaporization by Eq. (4.11) at one of the following temperatures and compare the result with the value calculated from the enthalpy values given in the table.

(*a*) 5(°F), (*b*) 30(°F), (*c*) 55(°F), (*d*) 80(°F), (*e*) 105(°F).

4.14. One hundred kmol per hour of subcooled liquid at 300 K and 3 bar is superheated to 500 K in a steady-flow heat exchanger. Estimate the exchanger duty (in kW) for one of the following:

(*a*) Methanol, for which $T^{\text{sat}} = 368.0$ K at 3 bar.
(*b*) Benzene, for which $T^{\text{sat}} = 392.3$ K at 3 bar.
(*c*) Toluene, for which $T^{\text{sat}} = 426.9$ K at 3 bar.

4.15. Saturated-liquid benzene at pressure $P_1 = 10$ bar ($T_1^{\text{sat}} = 451.7$ K) is throttled in a steady-flow process to a pressure $P_2 = 1.2$ bar ($T_2^{\text{sat}} = 358.7$ K), where it is a liquid/vapor mixture. Estimate the molar fraction of the exit stream that is vapor. For liquid benzene, $C_P = 162$ J mol^{-1} K^{-1}. Ignore the effect of pressure on the enthalpy of liquid benzene.

Due: 2-7-13 | $\boxed{\text{HW \#6}}$ | John Burke

$\frac{40}{40}$

$\boxed{7}$ State #1: 298.15 K, 121.3 kPa $\xrightarrow[\text{Adiabatic}]{\text{reversible/}}$ State #2: T_2, 101.3 kPa $\xrightarrow{\text{Constant V}}$ State #3: 298.15 K, 104.0 kPa

For ideal gas: $\frac{P_2\cancel{V_2}}{P_3\cancel{V_3}} = \frac{\cancel{R}T_2}{\cancel{R}T_3}$ $\quad P_2T_3 = P_3T_2$; $(101.3\text{ kPa})(298.15\text{ K}) = (104.0\text{kPa})\,T_2$

$\underline{T_2 = 290.41\text{ K}}$

For adiabatic process:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{R/C_p} \; ; \quad \frac{290.14\text{ K}}{298.15\text{ K}} = \left(\frac{101.3\text{kPa}}{121.3\text{kPa}}\right)^{\frac{(8.314\frac{J}{mol\,K})}{C_p}}$$

Thus,

$$0 = (0.8351195)^{\left(\frac{8.314\frac{J}{mol\,K}}{C_p}\right)} - 0.9731343$$

Using graphing calc to find zero:

$$\boxed{C_p = 56.92\ \frac{J}{mol\cdot K}}$$

✓

$\boxed{11}$ (Eq 4.13): $\frac{\Delta H_2}{\Delta H_1} = \left(\frac{1-T_{r2}}{1-T_{r1}}\right)^{0.38}$

(a) FOR CHLOROFORM: ΔH @ 0°C = 270.9 J/g
$T_n = 334.3$ K $\quad P_c = 54.72$ bar
$T_c = 536.4$ K

Thus,

$T_{R1} = \frac{273.15K}{536.4K} = 0.5092 = T_{R1}$

$T_{R2} = \frac{334.3K}{536.4K} = 0.6232 = T_{RN}$

and by equation 4.13:

$$\frac{\Delta H_N}{270.9\ J/g} = \left(\frac{1-0.6232}{1-0.5092}\right)^{0.38} \; ;$$

$\boxed{\text{CHLOROFORM}}$

$\boxed{\Delta H_N = 245\ J/g}$ ✓

* Only needed 1

(b) (Eq 4.12): $\frac{\Delta H_n}{RT_n} = \frac{1.092(\ln P_c - 1.013)}{0.930 - T_{RN}}$

$$\frac{\Delta H_n}{(8.314\frac{J}{mol\,K})(334.3K)} = \frac{1.092(\ln(54.72\text{ bar}) - 1.013)}{0.930 - 0.6232}$$

$$\Delta H_n = \left(29571.47\frac{J}{mol}\right)\left(\frac{1\text{ mol chloroform}}{119.377\text{ g}}\right) \; ;$$

✓

$\boxed{\Delta H_n = 247.7\ J/g}$

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COMPARISONS :

Tabulated value for chloroform : $\Delta H_{n_{Tab}} = \left(29.24 \frac{KJ}{mol}\right)\left(\frac{1000J}{1KJ}\right)\left(\frac{1mol}{119.377g}\right)$

$$\underline{\underline{\Delta H_{n_{Tab}} = 246.9 \ J/g}}$$

Part A: $\left(\frac{|245 \ J/g - 246.9 \ J/g|}{246.9 \ J/g}\right) \times 100\% = \boxed{-0.770 \ \% \text{ error for part (a)}}$ ✓

Part B: $\frac{(247.7 \ J/g - 246.9 \ J/g)}{246.9 \ J/g} \times 100\% = \boxed{0.33 \ \% \text{ error for part (a)}}$

→ CHLOROFORM

$\boxed{14}$ → on attached paper (MATHCAD)

$\boxed{15}$

$$\#1 \left\{ \begin{array}{l} \underline{\text{Saturated Liquid}} \text{ - Benzene} \\ P_1 = 10 \text{ bar} \\ T_1^{SAT} = 451.7 \text{ K} \end{array} \right. \Longrightarrow \left. \begin{array}{l} \underline{\text{liquid - vapor}} \\ P_2 = 1.2 \text{ bar} \\ T_2^{SAT} = 358.7 \text{ K} \end{array} \right\} \#2$$

* Cp liquid Benzene = 162 J/molK
↳ Ignore effect of Pressure of Cp

$$\Delta H + \Delta \overset{0}{\cancel{PE}} + \Delta \overset{0}{\cancel{KE}} = \overset{0}{\cancel{Q}} + \overset{0}{\cancel{W_s}}$$

Assumes Q, Ws, ΔPE, ΔKE = 0

$\Delta H = 0$

Also,

$$\frac{\Delta H_2}{\Delta H_1} = \left(\frac{1 - T_{R2}}{1 - T_{R1}}\right)^{0.38}$$

For Benzene :
MW = 78.114 g/mol
T_c = 562.2 K T_n = 353.2 K
P_c = 48.48 bar

$$\frac{\Delta H_n}{(8.314 \frac{J}{molK})(353.2K)} = \frac{1.092(\ln(48.98) - 1.013)}{0.930 - 0.6282}$$; $\Delta H_n = 30.588 \ KJ/mol$

Therefore : $\frac{\Delta H_2}{\Delta H_1} = \left(\frac{1 - T_{R2}}{1 - T_{R1}}\right)^{0.38}$

$\Delta H_2 = \Delta H_n = 30.588 \ KJ/mol$
$T_{R2} = T_{Rn} = 0.6282$
$T_{R1} = 358.7K / 562.2K = 0.6380$

$$\frac{30.588 \ KJ/mol}{\Delta H_1} = \left(\frac{1 - 0.6282}{1 - 0.6380}\right)^{0.38}$$

$$\Delta H_1 = \Delta H_{VAP @ 358.7K} = 30.28 \ KJ/mol$$

$\Delta H = 0$ (since adiabatic)

$$\Delta H = \int_{T_1}^{T_2} C_p \, dT = 0 \quad \text{or} \quad (X_{vap}) \Delta H_{vap @ 358.7K} = \int_{T_1}^{T_2} C_p \, dT$$

Thus,

$$-(X_{vap})\left(30.28 \frac{kJ}{mol}\right) = (358.7 - 451.7 \text{ K})(0.162 \text{ kJ/mol K})$$

$X_{vap} = 0.498$

Mole fraction of vapor in output stream

✓

14 . a

MCPH, ICPH Functions

$$\tau\left(T_0,T\right) := \frac{T}{T_0}$$

$$H_2\left(T_0,T,B\right) := \left(\frac{B}{2}\right)T_0\left(\tau\left(T_0,T\right)+1\right)$$

$$H_3\left(T_0,T,C\right) := \frac{C}{3}\left(T_0\right)^2\cdot\left[\tau\left(T_0,T\right)^2+\left(\tau\left(T_0,T\right)+1\right)\right]$$

$$H_4\left(T_0,T,D\right) := \frac{D}{\left(\tau\left(T_0,T\right)\right)}\cdot\left(T_0\right)^{-2}$$

$$S_2\left(T_0,T,C,D\right) := C\cdot\left(T_0\right)^2+\left[\frac{D}{\left[\tau\left(T_0,T\right)^2\cdot\left(T_0\right)^2\right]}\right]$$

$$S_3\left(T_0,T\right) := \frac{\left(\tau\left(T_0,T\right)+1\right)}{2}$$

$$S_4\left(T_0,T\right) := \frac{\left(\tau\left(T_0,T\right)-1\right)}{\ln\left(\tau\left(T_0,T\right)\right)}$$

$$\mathrm{MCPH}\left(T_0,T,A,B,C,D\right) := A+H_2\left(T_0,T,B\right)+H_3\left(T_0,T,C\right)+H_4\left(T_0,T,D\right)$$

$$\mathrm{ICPH}\left(T_0,T,A,B,C,D\right) := \mathrm{MCPH}\left(T_0,T,A,B,C,D\right)\cdot\left(T-T_0\right)$$

Problem 4.14 (Part A):

$\text{kmol} := 1000\text{mol}$ $T_{subliq} := 300\text{K}$ $P_{subliq} := 3\text{bar}$

$M_{feed} := 100\dfrac{\text{kmol}}{\text{hr}}$ $T_{super} := 500\text{K}$ $\text{KJ} := 1000\text{J}$

For Methanol:

Cp values for Liquid Methanol:

$T_{sat} := 368\text{K}$ $A := 13.431$ $B := -51.28\cdot 10^{-3}$ $C := 131.13\cdot 10^{-6}$ $D := 0$

$P_{sat} := 3\text{bar}$ $R_1 := 8.314\dfrac{\text{J}}{\text{mol}\cdot\text{K}}$

$T_c := 512.6\text{K}$ $P_c := 80.97\text{bar}$ $T_n := 337.9\text{K}$

$Q_1 := \text{MCPH}(368, 300, A, B, C, D)$ $Q_1 = 10.982$

$Q_{11} := 8.314\dfrac{\text{J}}{\text{mol}}\,\text{ICPH}(300, 368, A, B, C, D)$

For Subcooled Liquid

$$\boxed{Q_{11} = 6.209\frac{\text{KJ}}{\text{mol}}}$$

Cp values for Vapor Methanol:

$A_1 := 2.211$ $B_1 := 12.216\cdot 10^{-3}$ $C_1 := -3.45\cdot 10^{-6}$ $D_1 := 0$

$Q_2 := \text{MCPH}(500, 368, A_1, B_1, C_1, D_1)$ $Q_2 = 6.858$

$Q_{22} := 8.314\dfrac{\text{J}}{\text{mol}}\,\text{ICPH}(368, 500, A_1, B_1, C_1, D_1)$

For Superheated Methanol:

$$\boxed{Q_{22} = 7.526\frac{\text{KJ}}{\text{mol}}}$$

For heat of vaporization:

$T_r := \frac{T_n}{T_c}$ $T_r = 0.659$ $T_{rsat} := \frac{T_{sat}}{T_c}$ $T_{rsat} = 0.718$

$$\Delta H_n := \frac{\left[1.092 \cdot \left(\ln\left(\frac{P_c}{bar}\right) - 1.013\right)\right]}{\left(0.930 - T_r\right)} \cdot R_1 \cdot T_n \qquad \Delta H_n = 38.301 \frac{KJ}{mol}$$

$$\Delta H_v := \Delta H_n \cdot \left[\frac{\left(1 - T_{rsat}\right)}{\left(1 - T_r\right)}\right]^{.38} \qquad \Delta H_v = 35.645 \frac{KJ}{mol}$$

$KW := 1000W$

Total Energy Duty of Exchange:

$Energy := \left(\Delta H_v + Q_{11} + Q_{22}\right) \cdot M_{feed}$

$\boxed{Energy = 1.372 \times 10^3 \, KW}$ ✓

Homework #7

Problem statements.

4.30. Ammonia gas enters the reactor of a nitric acid plant mixed with 30% more dry air than is required for the complete conversion of the ammonia to nitric oxide and water vapor. If the gases enter the reactor at 75°C [167(°F)], if conversion is 80%, if no side reactions occur, and if the reactor operates adiabatically, what is the temperature of the gases leaving the reactor? Assume ideal gases.

✓**4.32.** A gas mixture of methane and steam at atmospheric pressure and 500°C is fed to a reactor, where the following reactions occur:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \text{and} \qquad CO + H_2O \rightarrow CO_2 + H_2$$

The product stream leaves the reactor at 850°C. Its composition (mole fractions) is:

$$y_{CO_2} = 0.0275 \qquad y_{CO} = 0.1725 \qquad y_{H_2O} = 0.1725 \qquad y_{H_2} = 0.6275$$

Determine the quantity of heat added to the reactor per mole of product gas.

4.39. A gas consisting only of CO and N_2 is made by passing a mixture of flue gas and air through a bed of incandescent coke (assume pure carbon). The two reactions that occur both go to completion:

$$CO_2 + C \rightarrow 2CO \qquad \text{and} \qquad 2C + O_2 \rightarrow 2CO$$

A ~~They yield~~ a flue gas of composition: 12.8 mol-% CO, 3.7 mol-% CO_2, 5.4 mol-% O_2, and 78.1 mol-% N_2. The flue gas/air mixture is so proportioned that the heats of the two reactions cancel, and the temperature of the coke bed is therefore constant. If this temperature is 875°C, if the feed stream is preheated to 875°C, and if the process is adiabatic, what ratio of moles of flue gas to moles of air is required, and what is the composition of the gas produced?

4.47. Quantitative thermal analysis has been suggested as a technique for monitoring the composition of a binary gas stream. To illustrate the principle, do one of the following problems.

(*a*) A methane/ethane gas mixture is heated from 25 to 250°C at 1(atm) in a steady-flow process. If $Q = 11,500$ J mol^{-1}, what is the composition of the mixture?

(*b*) A benzene/cyclohexane gas mixture is heated from 100 to 400°C at 1(atm) in a steady-flow process. If $Q = 54,000$ J mol^{-1}, what is the composition of the mixture?

(*c*) A toluene/ethylbenzene gas mixture is heated from 150 to 250°C at 1(atm) in a steady-flow process. If $Q = 17,500$ J mol^{-1}, what is the composition of the mixture?

5.8. With respect to 1 kg of liquid water:

(*a*) Initially at 0°C, it is heated to 100°C by contact with a heat reservoir at 100°C. What is the entropy change of the water? Of the heat reservoir? What is ΔS_{total}?

(*b*) Initially at 0°C, it is first heated to 50°C by contact with a heat reservoir at 50°C and then to 100°C by contact with a reservoir at 100°C. What is ΔS_{total}?

(*c*) Explain how the water might be heated from 0°C to 100°C so that $\Delta S_{\text{total}} = 0$.

5.10. An ideal gas, $C_P = (7/2)R$, is heated in a steady-flow heat exchanger from 70°C to 190°C by another stream of the same ideal gas which enters at 320°C. The flow rates of the two streams are the same, and heat losses from the exchanger are negligible.

(*a*) Calculate the molar entropy changes of the two gas streams for both parallel and countercurrent flow in the exchanger.

(*b*) What is ΔS_{total} in each case?

(*c*) Repeat parts (*a*) and (*b*) for countercurrent flow if the heating stream enters at 200°C.

5.12. For an ideal gas prove that:

$$\frac{\Delta S}{R} = \int_{T_0}^{T} \frac{C_V^{ig}}{R} \frac{dT}{T} + \ln \frac{V}{V_0}$$

John Burke

HW#7

SET 2

70/70

Problem 4.30:

$4\ NH_3(g) + 5\ O_2 \Longrightarrow 6\ H_2O(g) + 4\ NO(g)$

Relationships: 30% excess air, 80% conversion of $NH_3(g)$

Mass Balance: basis = 1 mole $NH_3(g)$

$NH3_{fed} := 1$

$O2_{fed} := 1 \cdot \frac{5}{4} \cdot 1.3$ $\qquad O2_{fed} = 1.625$

$N2_{fed} := \frac{O2_{fed}}{.21} \cdot .79$ $\qquad N2_{fed} = 6.113$

$NH3_{out} := 0.2 \cdot NH3_{fed}$ $\qquad NH3_{out} = 0.2$

$H2O_{out} := 0.8 \cdot NH3_{fed} \cdot \frac{6}{4}$ $\qquad H2O_{out} = 1.2$

$NO_{out} := 0.8 NH3_{fed} \cdot \frac{4}{4}$ $\qquad NO_{out} = 0.8$

guess

$N2_{out} := 1 \quad O2_{out} := 1$

given

$1 \cdot NH3_{fed} + 2 \cdot N2_{fed} = NH3_{out} + 2 \cdot N2_{out} + NO_{out}$

$2 \cdot O2_{fed} = 2 \cdot O2_{out} + H2O_{out} + NO_{out}$

$massBal := find(N2_{out}, O2_{out})$ $\qquad N2_{out} := massBal_0$

$O2_{out} := massBal_1$

Problem 4.32

Mass Balance:

basis = 1 mole of product gas

given

$CO2_{out} := 0.0275mol$ $CO_{out} := 0.1725mol$ $H2O_{out} := 0.1725mol$

$H2_{out} := 0.6275mol$

guess

$H2O_{fed} := 1mol$ $CH4_{fed} := 1mol$

$$2 \cdot H2O_{fed} + 4 \cdot CH4_{fed} = 2 \cdot H2O_{out} + 2 \cdot H2_{out}$$

$$CH4_{fed} = 1 \cdot CO2_{out} + 1 \cdot CO_{out}$$

$massBal := find(H2O_{fed}, CH4_{fed})$

$H2O_{fed} := massBal_0$ $H2O_{fed} = 0.4\,mol$

$CH4_{fed} := massBal_1$ $CH4_{fed} = 0.2\,mol$

Energy Balance: using method of heats of formation

CH4 Heats of Formation info:

$A_{CH4} := 1.702$ $B_{CH4} := 9.081 \cdot 10^{-3} K^{-1}$ $C_{CH4} := -2.164 \cdot 10^{-6} K^{-2}$

$\Delta H_{CH4} := -74520 \frac{J}{mol}$ $D_{CH4} := 0$

H2O Heats of Formation info:

$A_{H2O} := 3.470$ $B_{H2O} := 1.450 \cdot 10^{-3} K^{-1}$ $D_{H2O} := 0.121 \cdot 10^{5} K^{2}$

$\Delta H_{H2O} := -241818 \frac{J}{mol}$ $C_{H2O} := 0$

CO Heats of Formation info:

$A_{CO} := 3.376$ $B_{CO} := 0.557 \cdot 10^{-3} K^{-1}$ $D_{CO} := -0.031 \cdot 10^{5} K^{2}$

$\Delta H_{CO} := -110525 \frac{J}{mol}$ $C_{CO} := 0$

CO2 Heats of Formation info:

$A_{CO2} := 5.457$ $B_{CO2} := 1.045 \cdot 10^{-3} K^{-1}$ $D_{CO2} := -1.157 \cdot 10^{5} K^{2}$

$\Delta H_{CO2} := -393509 \frac{J}{mol}$ $C_{CO2} := 0$

H2 Heats of Formation info:

$A_{H2} := 3.249$ $B_{H2} := 0.422 \cdot 10^{-3} K^{-1}$ $D_{H2} := 0.083 \cdot 10^{5} K^{2}$

$\Delta H_{H2} := 0 \frac{J}{mol}$ $C_{H2} := 0$

Calculations for Reactions:

$$A_{rea} := \begin{pmatrix} A_{H2O} \\ A_{CH4} \end{pmatrix} \qquad B_{rea} := \begin{pmatrix} B_{H2O} \\ B_{CH4} \end{pmatrix} \qquad C_{rea} := \begin{pmatrix} C_{H2O} \\ C_{CH4} \end{pmatrix} \qquad D_{rea} := \begin{pmatrix} D_{H2O} \\ D_{CH4} \end{pmatrix}$$

$$n_{rea} := \begin{pmatrix} H2O_{fed} \\ CH4_{fed} \end{pmatrix} \qquad i := 0..1 \qquad R := 8.314 \frac{J}{mol \cdot K} \qquad KJ := 1000J$$

$$A_{reasum} := \sum_{i} \left(A_{rea_i} \cdot n_{rea_i} \right) \qquad A_{reasum} = 1.728\,mol$$

$$B_{reasum} := \sum_{i} \left(B_{rea_i} \cdot n_{rea_i} \right) \qquad B_{reasum} = 2.396 \times 10^{-3} \frac{mol}{K}$$

$$C_{reasum} := \sum_{i} \left(C_{rea_i} \cdot n_{rea_i} \right) \qquad C_{reasum} = -4.328 \times 10^{-7} \frac{mol}{K^2}$$

$$D_{reasum} := \sum_{i} \left(D_{rea_i} \cdot n_{rea_i} \right) \qquad D_{reasum} = 4.84 \times 10^{3}\,mol \cdot K^2$$

$$\Delta H_{reac1} := R \cdot MCPH(298.15K, 773.15K, A_{reasum}, B_{reasum}, C_{reasum}, D_{reasum}) \cdot (773.15K - 298.15K)$$

$$\Delta H_{reac1} = 11.455\,mol \frac{KJ}{mol} \qquad \Delta H_{reac2} := CH4_{fed} \cdot \Delta H_{CH4} + H2O_{fed} \cdot \Delta H_{H2O}$$

$$\Delta H_{reac} := \Delta H_{reac1} + \Delta H_{reac2} \qquad \Delta H_{reac} = -100.176\,KJ$$

Calculations for Products:

$$A_{prod} := \begin{pmatrix} A_{H2O} \\ A_{CO} \\ A_{CO2} \\ A_{H2} \end{pmatrix} \quad B_{prod} := \begin{pmatrix} B_{H2O} \\ B_{CO} \\ B_{CO2} \\ B_{H2} \end{pmatrix} \quad C_{prod} := \begin{pmatrix} C_{H2O} \\ C_{CO} \\ C_{CO2} \\ C_{H2} \end{pmatrix} \quad D_{prod} := \begin{pmatrix} D_{H2O} \\ D_{CO} \\ D_{CO2} \\ D_{H2} \end{pmatrix}$$

$$n_{prod} := \begin{pmatrix} H2O_{out} \\ CO_{out} \\ CO2_{out} \\ H2_{out} \end{pmatrix} \qquad i := 0..3$$

$$A_{prodsum} := \sum_i \left(A_{prod_i} \cdot n_{prod_i}\right) \qquad A_{prodsum} = 3.37\,\text{mol}$$

$$B_{prodsum} := \sum_i \left(B_{prod_i} \cdot n_{prod_i}\right) \qquad B_{prodsum} = 6.397 \times 10^{-4}\,\frac{\text{mol}}{\text{K}}$$

$$C_{prodsum} := \sum_i \left(C_{prod_i} \cdot n_{prod_i}\right) \qquad C_{prodsum} = 0$$

$$D_{prodsum} := \sum_i \left(D_{prod_i} \cdot n_{prod_i}\right) \qquad D_{prodsum} = 3.579 \times 10^{3}\,\text{mol} \cdot \text{K}^2$$

$$\Delta H_{prod1} := R \cdot MCPH\left(298.15K, 1123.15K, A_{prodsum}, B_{prodsum}, C_{prodsum}, D_{prodsum}\right) \cdot (1123.15K - 298.15K)$$

$$\Delta H_{prod1} = 26.305\,\text{KJ}$$

$$\Delta H_{prod2} := H2O_{out} \cdot \Delta H_{H2O} + CO2_{out} \cdot \Delta H_{CO2} + CO_{out} \cdot \Delta H_{CO} + H2_{out} \cdot \Delta H_{H2}$$

$$\Delta H_{prod} := \Delta H_{prod1} + \Delta H_{prod2} \qquad \Delta H_{prod} = -45.296\,\text{KJ}$$

Overall Energy Balance

$$Q := \Delta H_{prod} - \Delta H_{reac}$$

✓

$$\boxed{Q = 54.881\ \mathrm{KJ}}$$

Problem 4.39

$KJ := 1000J$

$R := 8.314\frac{J}{mol\cdot K}$

Reaction 1: CO2(g) + C(s) ==> 2CO(g) $\Delta H_{real1298} := 172.459\frac{KJ}{mol}$

Reaction 2: 2C(s) + O2(g) ==> 2CO(g) $\Delta H_{real2298} := -221.05\frac{KJ}{mol}$

CO heat capacity parameters:

$A_{CO} := 3.376$ $B_{CO} := 0.557\cdot 10^{-3}K^{-1}$ $C_{CO} := 0$ $D_{CO} := -0.031\cdot 10^{5}K^{2}$

CO2 heat capacity parameters:

$A_{CO2} := 5.457$ $B_{CO2} := 1.045\cdot 10^{-3}K^{-1}$ $C_{CO2} := 0$ $D_{CO2} := -1.157\cdot 10^{5}K^{2}$

O2 heat capacity parameters:

$A_{O2} := 3.639$ $B_{O2} := 0.506\cdot 10^{-3}K^{-1}$ $C_{O2} := 0$ $D_{O2} := -0.227\cdot 10^{5}K^{2}$

C heat capacity parameters:

$A_{C} := 1.771$ $B_{C} := 0.771\cdot 10^{-3}K^{-1}$ $C_{C} := 0$ $D_{C} := -0.867\cdot 10^{5}K^{2}$

Heat of Reaction for Reaction 1:

$i := 0..2$

$n_{reac1} := \begin{pmatrix} -1 \\ -1 \\ 2 \end{pmatrix}$ $A_{reac1} := \begin{pmatrix} A_{CO2} \\ A_C \\ A_{CO} \end{pmatrix}$ $B_{reac1} := \begin{pmatrix} B_{CO2} \\ B_C \\ B_{CO} \end{pmatrix}$ $C_{reac1} := \begin{pmatrix} C_{CO2} \\ C_C \\ C_{CO} \end{pmatrix}$

$D_{reac1} := \begin{pmatrix} D_{CO2} \\ D_C \\ D_{CO} \end{pmatrix}$

$A_{sumReac1} := \sum_i \left(A_{reac1_i} \cdot n_{reac1_i}\right)$ $C_{sumReac1} := \sum_i \left(C_{reac1_i} \cdot n_{reac1_i}\right)$

$B_{sumReac1} := \sum_i \left(B_{reac1_i} \cdot n_{reac1_i}\right)$ $D_{sumReac1} := \sum_i \left(D_{reac1_i} \cdot n_{reac1_i}\right)$

$\Delta H_{sumReac1} := R \cdot MCPH(298.15K, 1148.15K, A_{sumReac1}, B_{sumReac1}, C_{sumReac1}, D_{sumReac1})$

$\Delta H_{sumReac1} := R \cdot ICPH(298.15K, 1148.15K, A_{sumReac1}, B_{sumReac1}, C_{sumReac1}, D_{sumReac1})$

$\Delta H_{sumReac1} = -2.901 \frac{KJ}{mol}$

$\Delta H_{reac1875} := \Delta H_{sumReac1} + \Delta H_{rea1298}$

$\Delta H_{reac1875} = 169.558 \frac{KJ}{mol}$

Heat of Reaction for Reaction 2:

$i := 0..2$

$$n_{reac2} := \begin{pmatrix} -2 \\ -1 \\ 2 \end{pmatrix} \qquad A_{reac2} := \begin{pmatrix} A_{C} \\ A_{O2} \\ A_{CO} \end{pmatrix} \qquad B_{reac2} := \begin{pmatrix} B_{C} \\ B_{O2} \\ B_{CO} \end{pmatrix} \qquad C_{reac2} := \begin{pmatrix} C_{C} \\ C_{O2} \\ C_{CO} \end{pmatrix}$$

$$D_{reac2} := \begin{pmatrix} D_{C} \\ D_{O2} \\ D_{CO} \end{pmatrix}$$

$$A_{sumReac2} := \sum_{i} \left(A_{reac2_i} \cdot n_{reac2_i} \right) \qquad C_{sumReac2} := \sum_{i} \left(C_{reac2_i} \cdot n_{reac2_i} \right)$$

$$B_{sumReac2} := \sum_{i} \left(B_{reac2_i} \cdot n_{reac2_i} \right) \qquad D_{sumReac2} := \sum_{i} \left(D_{reac2_i} \cdot n_{reac2_i} \right)$$

$$\Delta H_{sumReac2} := R \cdot MCPH\left(298.15K, 1148.15K, A_{sumReac2}, B_{sumReac2}, C_{sumReac2}, D_{sumReac2}\right) \cdot ($$

$$\Delta H_{sumReac2} = -3.885 \frac{KJ}{mol}$$

$$\Delta H_{reac2875} := \Delta H_{sumReac2} + \Delta H_{real2298}$$

$$\boxed{\Delta H_{reac2875} = -224.935 \frac{KJ}{mol}}$$

Basis = 100 mole flue gas

$$\text{ratio} := \frac{-\Delta H_{reac2875}}{\Delta H_{reac1875}} \qquad \underline{\underline{\text{ratio} = 1.327}}$$

Thus:

guess

$\text{Air}_{fed} := 1$

Given

$$\text{ratio} = \frac{12.8}{5.4 + 0.21 \cdot \text{Air}_{fed}}$$

Solution shown in class used 12.5? I think they entered wrong # for CO_2.

$\text{Air}_{fed} := \text{Find}(\text{Air}_{fed})$

$\text{Air}_{fed} = 20.232 \text{ mol}$

$$\text{FlueGasRatio} := \frac{100\text{mol}}{20.232\text{mol}} \qquad \boxed{\text{FlueGasRatio} = 4.943}$$

[redacted]

$\text{moles}_{CO} := 2(5.4 + 0.21 \cdot 19.155 + 3.7) + 12.8$

$\text{moles}_{CO} = 39.045 \text{ mol}$

$\text{moles}_{N2} := 19.155 \cdot .79 + 78.1$

$\text{moles}_{N2} = 93.232 \text{ mol}$

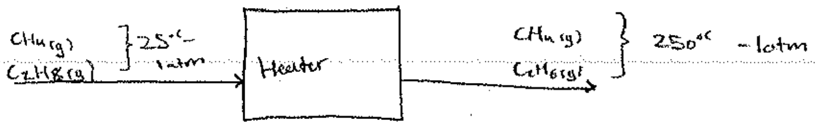
$$\text{comp}_{CO} := \frac{\text{moles}_{CO}}{\text{moles}_{CO} + \text{moles}_{N2}} \qquad \boxed{\text{comp}_{CO} = 0.295}$$

[redacted]

$$\text{comp}_{N2} := 1 - \text{comp}_{CO} \qquad \boxed{\text{comp}_{N2} = 0.705}$$

47 (a)

BASIS: 1mole feed / product



$\Delta H = Q + \cancel{W_s}^{0}$; $\Delta H = 11,500$ J/mol

	moles In	$\hat{H}_{In}$	moles Out	$\hat{H}_{out}$
$CH_{4(g)}$	n_1	0	n_1	$\hat{H}_1$
$C_2H_{8(g)}$	n_2	0	n_2	$\hat{H}_2$

$$\hat{H}_1 = R\int_{248.15K}^{523.15K} \left(1.702 + 9.081\times10^{-3}T - 2.164\times10^{-6}T^2\right)dT$$

$\hat{H}_1 = R\left[1137.84 \text{ K}\right]$; $\hat{H}_1 = (8.314 \text{ J/mol K})(1137.84 \text{ K})$

$\hat{H}_1 = 9.46$ KJ/mol

$$\hat{H}_2 = R\int_{298.15K}^{523.15K} \left(1.131 + 19.225\times10^{-3}T - 5.561\times10^{-6}T^2\right)dT$$

$\hat{H}_2 = (8.314 \text{ J/mol K})(1814.516 \text{ K})$; $\hat{H}_2 = 15.086$ KJ/mol

Energy Balance:

① $n_1(9.46 \text{ KJ/mol}) + n_2(15.086 \text{ KJ/mol}) = (+11.500 \text{ KJ/mol})\,1 \text{ mol}$

② $n_1 + n_2 = 1$

Thus,

$9.46 \text{ KJ/mol} - (9.46 \text{ KJ/mol})n_2 + (15.086 \text{ KJ/mol})n_2 = 11.500 \text{ KJ}$

$n_2 = 0.363$

$n_1 = 0.637$

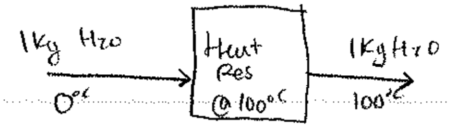
Thus, mixture comp:

36.3% $C_2H_{6(g)}$
63.7% $CH_{4(g)}$

5.8

$C_{p\,H_2O(l)} = 4.184\ kJ/KgK$

(a)



$$\Delta S^t = m\int \frac{C_p dT}{T} = mC_p \ln\frac{T_2}{T_1}$$

For water: $\frac{\Delta S^t}{m} = \left(4.184 \frac{KJ}{KgK}\right)\ln\left[\frac{373.15K}{273.15K}\right]$; $\boxed{\Delta S_{water} = +1.305 \frac{KJ}{KgK}}$

For reservoir: $\frac{\Delta S^t}{m} = \frac{-|Q|}{T}$ } Since heat is being lost "Hot Reservoir"

$Q = \Delta H_{water}$; $Q = (4.184\ KJ/KgK)(100\ K)$; $Q = 418.4\ KJ/Kg$

$$\Delta S = \frac{-418.4\ KJ/Kg}{373.15K} \quad ; \quad \boxed{\Delta S_{reservoir} = -1.121 \frac{KJ}{KgK}}$$

$$\Delta S_{total} = \left(+1.305 \frac{KJ}{KgK}\right) - \left(1.121 \frac{KJ}{KgK}\right) \quad ; \quad \boxed{\Delta S_{total} = 0.184 \frac{KJ}{KgK}}$$

(b) For water: ΔS will bethe same thus, $\Delta S_{water} = +1.305\ KJ/KgK$

For Reservoir: $\Delta S_{Step 1} = \frac{-|Q|}{T_1} = -\frac{(418.4\ KJ/Kg)(0.5)}{323.15K} = -0.6474\ KJ/KgK$

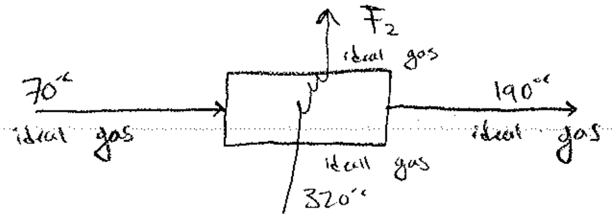
$$\Delta S_{Step 2} = \frac{(-418.4\ KJ/Kg)0.5}{373.15\ K} = -0.5606\ KJ/KgK$$

$$\Delta S_{Res} = -1.208\ KJ/KgK$$

$$\Delta S_{total} = -1.208\ KJ/KgK + 1.305\ KJ/KgK \quad ; \quad \boxed{\Delta S_{total} = +0.097 \frac{KJ}{KgK}}$$

(c) As can be seen from (b) and (a), increasing the temperature in multiple steps, rather than 1 step lowers the total change in entropy. Thus, creating a process with infinite number of infintesmally small temperature changes will set $\Delta S_{total} = 0$. Process is said to be reversible.

$\boxed{5.10}$



$Q=0$
$C_p = 7/2 R$

(a) For ideal gas: $\Delta S = \int_{T_0}^{T_1} C_p \frac{dT}{T} \Rightarrow RC_p \ln\left(\frac{T_2}{T_1}\right)$

☆ Since heat is not lost through reactor, heat lost from gas @ 320°C must be gained by gas @ 70°C. Therefore, since both gases are the same, the temperature changes are the same for <u>both</u> gases. This is true <u>regardless</u> of flow.

Thus, T_2 of gas entering @ 320°C will be <u>200°C</u> for both parallel and countercurrent flow!

<u>Gas 70°C ⟶ 190°C</u>

$$\Delta S = \left[\frac{7}{2}\, 8.314 \frac{J}{mol\,K}\right] \ln\left(\frac{463.15\,K}{343.15\,K}\right)$$

$$\boxed{\Delta S = 8.726 \frac{J}{mol\,K}}$$ ☆ FOR BOTH CASES ☆

<u>Gas 320°C ⟶ 200°C:</u>

$$\Delta S = \left[\frac{7}{2}\left(8.314 \frac{J}{mol\,K}\right)\right] \ln\left(\frac{473.15\,K}{593.15\,K}\right)$$

$$\boxed{\Delta S = -6.577\ J/mol\,K}$$ ☆ FOR BOTH CASES ☆

(b)

$$\Delta S_{total} = -6.577\ J/mol\,K + 8.726 \frac{J}{mol\,K}$$

$$\boxed{\Delta S_{total} = 2.149\ J/mol\,K}$$ ☆ FOR BOTH CASES ☆

(c)

<u>Gas 70°C ⟶ 190°C</u>

$$\boxed{\Delta S = 8.726\ J/mol\,K}$$

Gas 200°C → 80°C :

$$\Delta S = \left[\tfrac{7}{2}\left(8.314 \tfrac{J}{mol\,K}\right)\right] \ln\left(\frac{353.15\,K}{473.15\,K}\right)$$

$$\boxed{\Delta S = -8.512\ J/mol\,K}$$

$$\Delta S_{total} = -8.512 \frac{J}{mol K} + 8.726 \frac{J}{mol K}\ ; \quad \boxed{\Delta S_{total} = 0.214 \frac{J}{mol K}}$$

5.12 From text book:

$$\frac{dS}{R} = \frac{C_p^{i.g.}}{R}\frac{dT}{T} - \frac{dP}{P}$$

For ideal Gas:

$$PV = RT \quad /or/ \quad \ln(P) + \ln(V) = \ln(R) + \ln(T)$$

differentiating ideal gas gives: $\frac{1}{P}dP + \frac{1}{V}dV = \frac{1}{T}dT$

Rearranging gives: $\frac{dP}{P} = \frac{dT}{T} - \frac{dV}{V}$

Thus, substituting back into 1st equation:

$$\frac{dS}{R} = \frac{C_p^{i.g.}}{R}\frac{dT}{T} - \frac{dT}{T} + \frac{dV}{V} \quad /or/ \quad \frac{dS}{R} = \frac{dT}{T}\left[\frac{C_p^{i.g.}}{R} - 1\right] + \frac{dV}{V}$$

Correlation between $C_p^{i.g.}$ and $C_v^{i.g.}$:

$$C_p^{i.g.} = C_v^{i.g.} + R \quad /or/ \quad \frac{C_p^{i.g.}}{R} = \frac{C_v^{i.g.}}{R} + 1 \quad /or/ \quad \frac{C_p^{i.g.}}{R} - 1 = \frac{C_v^{i.g.}}{R}$$

Substitution leads to:

$$\frac{dS}{R} = \frac{dT}{T}\left[\frac{C_v^{i.g.}}{R}\right] + \frac{dV}{V}$$

* note: $\frac{dV}{V}$ can be written as $d(\ln V)$

Hence,

$$\frac{dS}{R} = \frac{C_v^{i.g.}}{R}\frac{dT}{T} + d\ln(V)$$

Integration yields:

$$\boxed{\frac{\Delta S}{R} = \int_{T_0}^{T} \frac{C_v^{i.g.}}{R}\frac{dT}{T} + \ln\left(\frac{V}{V_0}\right)}$$