Perspectives on Thermodynamics Instruction

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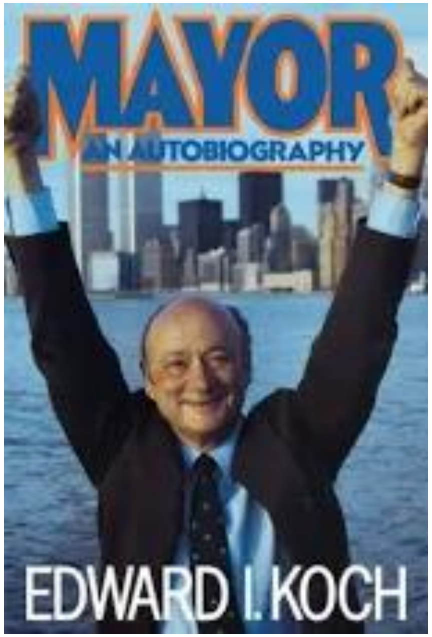
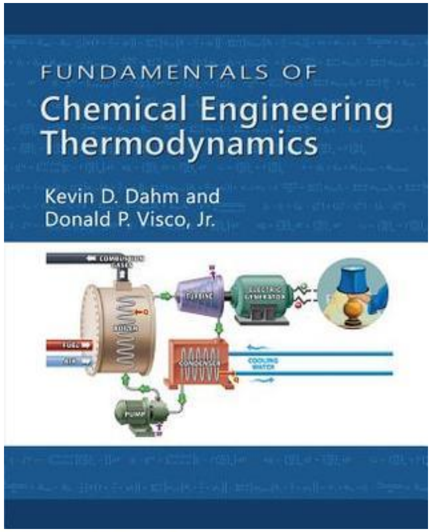
Rowan University

The University of Akron
College of Engineering

What to talk about in this venue?

- Ed Koch
- Fifty minutes on the virtue of our text book?
- We decided, after much discussion, to focus this presentation on areas that you may not know a lot about as it relates to thermodynamics instruction/education
- It was a good learning experience for both of us and expanded our minds





I hate thermodynamics, and some motivation will help self.AskEngineers
submitted 10 months ago by yogo98

1

Hey guys, I have a really hard time learning thermodynamics and if some of you could give me some examples of how it helped you, I would be grateful (because currently I have this "I don't really need it" feeling, which makes it so difficult to study). Thanks

9 comments share save hide report

Forums Social OT Discussion Club

Dang, I really suck at Thermodynamics

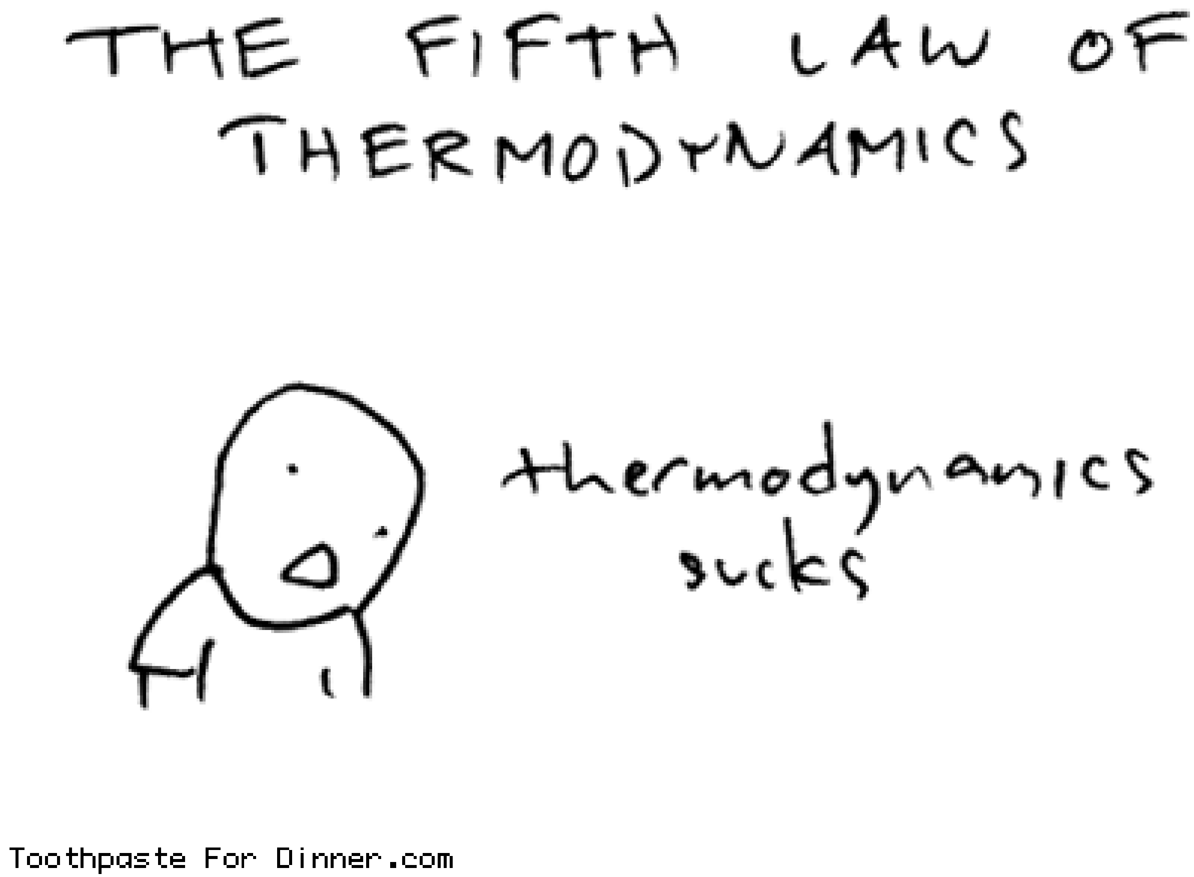
Discussion in 'OT Discussion Club' started by NaOH, Dec 19, 2006.

Science & Mathematics Engineering

I hate Thermodynamics!!!! please help!!!!?

He thinks people who do things like accountancy and psychology, well pretty much all of the business and most of the arts students aren't very smart. To be honest, I had a quick glance at some of the accounting and psychology material and there's no way that's more difficult than most of the sciences, especially thermodynamics. Crap how I hate thermodynamics.

First day of class…


THE FIFTH LAW OF THERMODYNAMICS
thermodynamics sucks
Toothpaste For Dinner.com

CHEMICAL THERMODYNAMICS

We are happy to report that Rubin Battino, of Wright State University, Dayton, Ohio, has picked up the chemical thermodynamics ball. Although neither he nor the AC_3 was able to find funds for a workshop-type session to explore the modern teaching of thermodynamics, he has arranged a most promising session for the Fall, 1969 ACS meeting.

The symposium on the teaching of thermodynamics will be held under the sponsorship of the Division of Chemical Education of the American Chemical Society in New York City in September. The day allotted for the symposium is Wednesday, September 10. The program is divided into three quarter-day sessions with three invited speakers in each session. Since the subject of chemical thermodynamics is so central to chemical engineering curricula, a chemical engineer has been invited to participate in each session.

The first session is on the relevance of thermodynamics to chemists and chemical engineers. It will be chaired by Prof. Mark W. Zemansky and the speakers will be Dr. L. K. Nash, Dr. E. E. Wood, and Dr. H. C. Van Ness. The second session is on the place of thermodynamics in the curriculum. The speakers in this session are Dr. H. A. Bent, Dr. N. Craig, and Dr. J. J. Martin. The third session is on methods of teaching thermodynamics and the speakers are Dr. C. E. Wales, Dr. W. H. Eberhardt, and Dr. R. C. Plumb.

About 50 years ago, we have evidence that Hank Van Ness was working with chemists in ACS to discuss "*the relevance of thermodynamics to chemists and chemical engineers*"

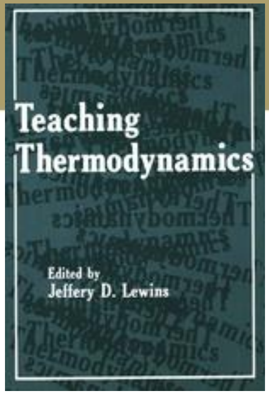
Interest in teaching thermodynamics

"It seemed appropriate to arrange a meeting of teachers of thermodynamics in the United Kingdom, a meeting held in the pleasant surroundings of Emmanuel College, Cambridge, in September, 1984. This volume records the ideas put forward by authors, the discussion generated and an account of the action that discussion has initiated. Emphasis was placed on the Teaching of Thermodynamics to degree-level students in their first and second years."

-- Preface to Teaching Thermodynamics,
Edited by Jeffery Lewins (1985)

UK engineering faculty (ME and ChE) – Sept. 1984

Monograph publication



1. Teaching Objectives
   - *"Why has Thermodynamics become a 'Difficult' Subject?"* – B.R. Wakeford
2. Innovative Methods of Teaching
   - "*Thermodynamics for Those Who Think with Their Fingers*" – C.S. Sharma
3. Computer Oriented and Laboratory Oriented Demonstrations
   - "*The Use of TV and Audio-Cassettes in Teaching Thermofluid Mechanics*" – W. K. Kennedy
4. Principles of Thermodynamics
   - "*Teaching Thermodynamics to First-Year Students by the Single-Axiom Approach*" – R.W. Haywood
5. Application of Thermodynamics to Design Assessment
   - "*Teaching the Exergy Method to Engineers*" – T. J. Kotas
6. Syllabus Development
   - *"Can Thermodynamics be Made more Simple?"* – M. D. Dampier

Engineering and related disciplines

- Many important/foundational/basic/confusing topics
  - First Law
  - Energy
  - Second Law
  - Entropy
  - Etc.
- There is (and has been) a vast interest in this over several decades
  - Impacts many disciplines beyond chemical engineering
    - Other engineering, especially mechanical engineering
    - Chemistry
    - Physics
    - Even biology
      - "*Biologists study the five principles of biology including cell theory, gene theory, homeostasis, evolution and energy and thermodynamics*" – **Valdosta State University**

Thermodynamics Education Literature:

Topics and Disciplines (Dreyfus et al., *AJP*, **83**, 5, 2015)

	Engineering	Chemistry	Physics	Biology
General/Overall	4	5	4	1
Gas Law/Kinetic Theory	0	3	7	0
Energy (General)	0	1	14	2
Heat and Temperature	1	5	26	0
Chemical Bonding/Chemical Energy	0	14	1	2
1st Law of Thermodynamics	0	10	16	0
Entropy and the Second Law	1	16	29	2
Probability/Statistics and the Second Law	0	1	3	1
Free Energy and the Second Law	0	13	0	0
Osmosis, Diffusion and Randomness	0	0	1	15
TOTAL	6	68	101	23

Thermodynamics Education Literature:

Topics and Disciplines (Dreyfus et al., *AJP*, **83**, 5, 2015)

	Engineering	Chemistry	Physics	Biology
General/Overall	4	5	4	1

Engineering

"**Identifying and repairing student misconceptions in thermal and transport science: Concept inventories and schema training studies**," R. L. Miller, R. A. Streveler, D. Yang, and A. I. Santiago Roman, *Chem. Eng. Educ*. 45, 203–210 (2011).

Chemistry

"**Difficulties of students from the faculty of science with regard to understanding the concepts of chemical thermodynamics**," H. Sokrat, S. Tamani, M. Moutaabbid, and M. Radid, Procedia - Soc. Behav. Sci. 116, 368–372 (2014)

Physics

"**Investigation of student learning in thermodynamics and implications for instruction in chemistry and engineering**," D. E. Meltzer, AIP Conf. Proc. 883, 38–41 (2007).

Biology

"**Building a foundation for bioenergetics**," E. Hamori, Biochem. Mol. Biol. Educ. 30, 296–302 (2002).

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	Engineering	Chemistry	Physics	Biology
Gas Law/Kinetic Theory	0	3	7	0

Engineering

Chemistry

“**The assessment of students and teachers’ understanding of gas laws**,” H.-S. Lin, H.-J. Cheng, and F. Lawrenz, J. Chem. Educ. 77, 235–238 (2000).

Physics

“**Student understanding of the ideal gas law, Part II: A microscopic perspective**,” C. H. Kautz, P. R. L. Heron, P. S. Shaffer, and L. C. McDermott, Am. J. Phys. 73, 1064–1071 (2005).

Biology

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	Engineering	Chemistry	Physics	Biology
Energy (General)	0	1	14	2

Engineering

Chemistry

"**Heat and work are not 'forms of energy**,'" G. D. Peckham and I. J. McNaught, J. Chem. Educ. 70, 103–104 (1993).

Physics

"**Students' difficulties with energy and related concepts**," H. Goldring and J. Osborne, Phys. Educ. 29, 26–32 (1994)

Biology

"**Diagnosing students' understanding of energy and its related concepts in biological context**," V. M. Chabalengula, M. Sanders, and F. Mumba, Int. J. Sci. Math. Educ. 10, 241–266 (2012)

Thermodynamics Education Literature:

Topics and Disciplines (Dreyfus et al., *AJP*, **83**, 5, 2015)

	Engineering	Chemistry	Physics	Biology
Heat and Temperature	1	5	26	0

Engineering

"**Misconceptions about rate processes: Preliminary evidence for the importance of emergent conceptual schemas in thermal and transport sciences**," R. Miller, M. Chi, M. Nelson, and M. Geist, in ASEE Conference Proceedings (2006)

Chemistry

"Can the study of thermochemistry facilitate students' differentiation between heat energy and temperature?" M. Niaz, J. Sci. Educ. Technol. 15, 269–276 (2006)

Physics

"**An attempt to overcome alternative conceptions related to heat and temperature**," M. F. Thomaz, I. M. Malaquias, M. C. Valente, and M. J. Antunes, Phys. Educ. 30, 19–26 (1995)

Biology

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Chemical Bonding/Chemical Energy	0	14	1	2

Engineering

Chemistry

"**A new road to reactions. Part 3. Teaching the heat effect of reactions**," W. de Vos and A. H. Verdonk, J. Chem. Educ. 63, 972–974 (1986)

Physics

"**Chemical energy in an introductory physics course for life science students**," B. W. Dreyfus, J. Gouvea, B. D. Geller, V. Sawtelle, C. Turpen, and E. F. Redish, Am. J. Phys. 82, 403–411 (2014)

Biology

"**Textbook errors & misconceptions in biology: Cell energetics**," R. D. Storey, Am. Biol. Teach. 54, 161–166 (1992)

Thermodynamics Education Literature:

Topics and Disciplines (Dreyfus et al., *AJP*, **83**, 5, 2015)

	Engineering	Chemistry	Physics	Biology
1st Law of Thermodynamics	0	10	16	0

Engineering

Chemistry

"**Effect of a dynamic learning tutorial on undergraduate students' understanding of heat and the first law of thermodynamics**," J. Barbera and C. E. Wieman, Chem. Educator 14, 45–48 (2009).

Physics

"**Critique of the treatment of work**," S. G. Canagaratna, Am. J. Phys. 46, 1241–1244 (1978).

Biology

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	Engineering	Chemistry	Physics	Biology
Entropy and the Second Law	1	16	29	2

Engineering

"**Probing student understanding of basic concepts and principles in introductory engineering thermodynamics**," C. H. Kautz and G. Schmitz, in ASME 2007 International Mechanical Engineering Congress and Exposition (2007), pp. 473–480

Chemistry

"**Entropy is simple, qualitatively**," F. L. Lambert, J. Chem. Educ. 79, 1241–1246 (2002).

Physics

"**Thermodynamic entropy: The spreading and sharing of energy**," H. S. Leff, Am. J. Phys. 64, 1261–1271 (1996).

Biology

"**Molecular thermodynamics for cell biology as taught with boxes**," L. S. Mayorga, M. J. Lopez, and W. M. Becker, CBE Life Sci. Educ. 11(1), 31–38 (2012).

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Topics and Disciplines (Dreyfus et al., *AJP*, **83**, 5, 2015)

	Engineering	Chemistry	Physics	Biology
Probability/Statistics and the Second Law	0	1	3	1

Engineering

Chemistry

"**An integrated, statistical molecular approach to the physical chemistry curriculum**," S. F. Cartier, J. Chem. Educ. 86, 1397–1402 (2009).

Physics

"**Student understanding of basic probability concepts in an upper-division thermal physics course**," M. E. Loverude, AIP Conf. Proc. 1179, 189–192 (2009)

Biology

"Understanding randomness and its impact on student learning: Lessons learned from building the Biology Concept Inventory (BCI)," K. Garvin-Doxas and M. W. Klymkowsky, CBE Life Sci. Educ. 7(2), 227–233 (2008).

Thermodynamics Education Literature:

Topics and Disciplines (Dreyfus et al., *AJP*, **83**, 5, 2015)

	Engineering	Chemistry	Physics	Biology
Free Energy and the Second Law	0	13	0	0

Engineering

Chemistry

"**Turkish chemistry undergraduate students' misunderstandings of Gibbs free energy,**" M. Sozbilir, Univ. Chem. Educ. 6(2), 73–83 (2002);

Physics

Biology

Thermodynamics Education Literature:

Topics and Disciplines (Dreyfus et al., *AJP*, **83**, 5, 2015)

	Engineering	Chemistry	Physics	Biology
Osmosis, Diffusion and Randomness	0	0	1	15

Engineering

Chemistry

Physics

"**Five popular misconceptions about osmosis**," E. M. Kramer and D. R. Myers, Am. J. Phys. 80, 694–699 (2012).

Biology

"**Students' misconceptions about diffusion: How can they be enhanced**," E. A. Marek et al., Am. Biol. Teach. 56, 74–77 (1994).

Some takeaways from that literature review

1. There is vast interest in thermodynamics teaching and learning outside of engineering
    - While many schools offer engineering and some offer chemical engineering, almost all schools will have chemistry, physics and biology programs.
2. The interest outside of engineering has existed for many decades and seemingly is only increasing
3. The interest is across most of the world
4. In many cases (and more recently), the articles are investigations with clearly defined research questions and a contextualized literature review

What is known about students and learning thermodynamics?

- There have been many studies on a variety of topics.
- In some cases, several studies reach the same conclusion.
- In other cases, studies reach different conclusions (and, sometime, opposing conclusions).

- We will mention a *few* to give you a flavor for the diversity of interest in this topic.

- We won't talk about the work Dr. Vigeant presented on yesterday.

High School Students in Turkey

- 418 HS students in Istanbul, Turkey
- Used the "Conceptual Understanding Test" → 30 MCQ
- Test given the end of the subject (not just a single grade)

Poor understanding of:

- Energy, enthalpy and bonds in chemical reactions
- Energy and catalysts in chemical reactions
- Changes in heat, temperature and enthalpy during change of state
- Relationship between heat, temperature, mass and specific heat.

H. Saricayir et al., "Determining Students' Conceptual Understanding Level of Thermodynamics, *J. Education and Training Studies*, **4**, 69 – 79 (2016).

Physics Community; multiple courses

- About 90 students across ME, ChE and Phys (five different courses).
- Used short-answer questions (with explanations) and classroom observation (with field notes).
- Focused on 1st Law and graphical interpretation of P-V diagrams

Results:

- Nothing unique about student difficulties in ME, ChE or Phys, though prevalence varies based on discipline
  - Different disciplines approached problems differently
  - ChEs described internal energy as a state function
- Work is "path-independent" was a prominent difficulty (treated as a state function)

J. Clark, J. Thompson and D. Mountcastle, "Investigating Student Conceptual Difficulties in Thermodynamics Across Multiple Disciplines: The First Law and P-V Diagrams" , *ASEE Conference Proceedings*, (2014)

Thailand (Physics)

- 46 students taking a first-year physics course
- Student responses to a various questions were used as well as qualitative interview data
- Questions were from the author-designed Thermodynamic Diagnostic Test

Results:

- Entropy-related alternative conceptions tend to stick even after instruction
- Instruction helped mitigate alternative conception of work as a state variable
- Pressure/temperature alternative conceptions hard to remove; PV=nRT is commonly used regardless of state

C. Kamcharean and P. Wattanakasiwich, "Development and Implication of a Two-tier Thermodynamics Diagnostic Test to Survey Students' Understanding in Thermal Physics", *Int. J. of Innovation in Sci. & Math Ed.* **24**, *14-36*, (2016)

Canada (Mechanical Engineering)

- *"…overview is presented of the most frequent thermodynamics misconceptions among engineering students*."
- Results from literature review…and perspective of author

Misconceptions/Alternate Conceptions:

- Heat is treated as an entity as opposed to a process
- Relationship between heat and temperature, especially adiabatic and isothermal processes
- Entropy as "visual disorder" of particles as opposed to freedom of movement of particles and access to additional energy levels

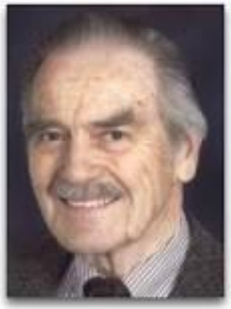
S. Fouroushani, "Misconceptions in engineering thermodynamics: A review", *Int. J. of Mech. Engr. Ed.* (2018)
https://doi.org/10.1177/0306419018754396

US (Chemistry → review)

- Thorough review in 2014 of discipline-based education research (DBER) within chemistry, physics, engineering and mathematics communities.
- Review "*many of the thermodynamic conceptions reported in the DBER literature*"
  <u>Results</u>:
- If a desire is to understand thermodynamics through use of mathematical relationships (e.g. Maxwell relationships), it is important for students to learn meanings of these concepts within the context of thermodynamics
- No heat transfer occurs under isothermal conditions
- System / universe confusion in describing entropy and 2nd Law
- At chemical equilibrium, most/all chemical reaction ceases
- If a reaction occurs fast, it goes towards full completion
- A substance cannot exist in the vapor phase below its boiling point

K. Bain et al., "A review of research on the teaching and learning in thermodynamics at the university level", *Chemistry Education Research and Practice*, **15**, 320 – 335 (2014).

Entropy…and disorder?



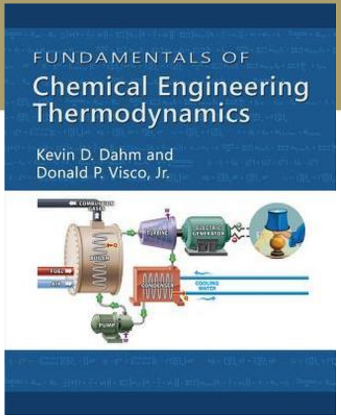
- While others have rejected the use of disorder in any description of entropy, Frank Lambert has been especially vigilant at this.   entropysite.oxy.edu
  - Chemistry Professor from Occidental College
  - Has counted 36 textbooks that have removed the description of disorder associated with entropy (as of 2014).
  - Calls the disorder description a “cracked crutch”.
  - You can lose yourself at that website (above).

Does the disorder description of entropy have any value?

- Jesper Haglund (post-doc / Phys education research at Uppsala University)
- Interesting research into the question of analogies as it relates to entropy concepts and how student ideas about entropy change during instruction
- Finds the following
  - A majority of students relate disorder to entropy, even after instruction
  - Many students realize that there is a problem with this relationship, however (i.e. it is an incomplete picture)
  - No relationship between conceptualization and exam scores
  - Entropy as disorder can be a useful stepping-stone

J. Haglund et al., “Chemical engineering students’ ideas of entropy”, *Chemistry Education Research and Practice*, **16**, 537 – 551 (2015).

What do we propose?



- Approach it in an applied engineering way
- Example using multiple output conditions of a turbine
  - First Law will allow you to solve the problem and obtain a shaft work value as a function of output conditions
  - Second Law puts a constraint (via entropy) on what the output conditions can be
  - Motivates the value of entropy and the Second Law
- We do comment on how the disorder analogy confirms what is observed (e.g. $S_{vapor} > S_{liquid} > S_{solid}$)
- Introduce concept of microstates and macrostates after the engineering example
  - Chapter 4 of the book is devoted entirely to entropy

Examples – Reversibility and Reversible Work

- Pal (2017) explored definitions and use of reversibility.
- Notes that "reversible" processes in some textbook examples/definitions are not truly reversible:

"Such an expansion process carried out quasi-statically could be referred to as a reversible process… This process would be truly reversible only if the heat is also exchanged reversibly."

R. Pal, "Conceptual issues related to reversibility and reversible work produced in closed and open flow systems", *Education for Chemical Engineers*, **19**, 29-37 (2017).

Examples – Reversibility and Reversible Work

- Mathematical illustration that "reversible work" is a state property if the process is truly reversible.

"A reversible process is one which does not destroy any exergy anywhere in the system or in the surroundings. In other words, the exergy of the thermodynamic universe is conserved during a reversible process. There occurs no net decrease in the exergy (useful work potential) of the universe due to a reversible process"

R. Pal, "Conceptual issues related to reversibility and reversible work produced in closed and open flow systems", *Education for Chemical Engineers*, **19**, 29-37 (2017).

Examples – Reversibility and Reversible Work

Two moles of an ideal gas are confined in a piston-cylinder device, initially at $P = 5$ bar and $T = 300$ K. The atmosphere is at $P = 1$ bar but there is a pile of sand on top of the piston, as shown in Figure 4-3. The mass of the sand is sufficient to make the total downward pressure on the piston 5 bar. The grains of sand are removed one at a time, leading to a gradual decrease in pressure and a gradual expansion of the gas, until the gas is at $P = 1$ bar. The temperature of the gas is $T = 300$ K throughout.

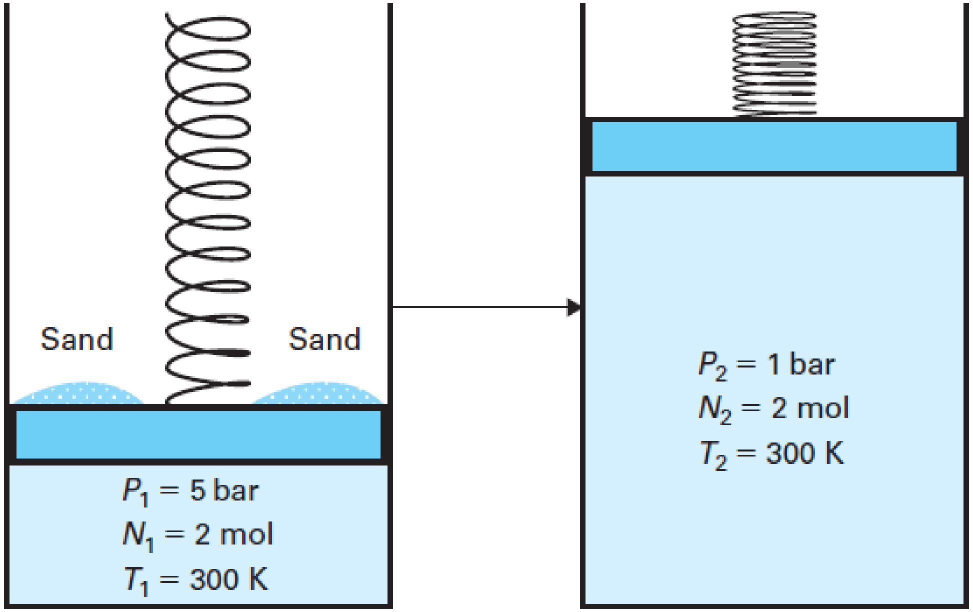


FIGURE 4-3 Reversible expansion process described in Example 4-3.

Examples – Use of some applications

- Bansagi and Rogers developed three separate apps for liquid-liquid equilibrium
  - Drawing a ternary phase diagram
  - Single stage LLE
  - Multi-stage LLE

- Survey data demonstrates that students found these apps beneficial

T. Bansagi and T. Rodgers, “Graphic web–apps for teaching ternary diagrams and liquid–liquid extraction”, *Education for Chemical Engineers*, **22**, 27-34 (2018).

Examples – Use of APPs

Equilibrium miscibility data		
Water	Ethylene Glycol	Furfural
5.0	0.0	95.0
4.5	5.2	90.3
4.1	11.5	84.4
4.9	20.0	75.1
5.8	27.5	66.7
9.5	41.5	49.0
15.2	50.5	34.3
20.0	52.5	27.5
38.6	47.5	13.9
49.0	40.0	11.0
60.3	30.0	9.7
76.6	15.0	8.4
92.3	0.0	7.7

Mutual equilibrium data	
Ethylene Glycol in Water	Ethylene Glycol in Furfural
52.5	27.5
51.5	20.0
47.5	15.0
40.0	10.0
30.0	7.5
20.0	6.2
15.0	5.2
7.3	2.5

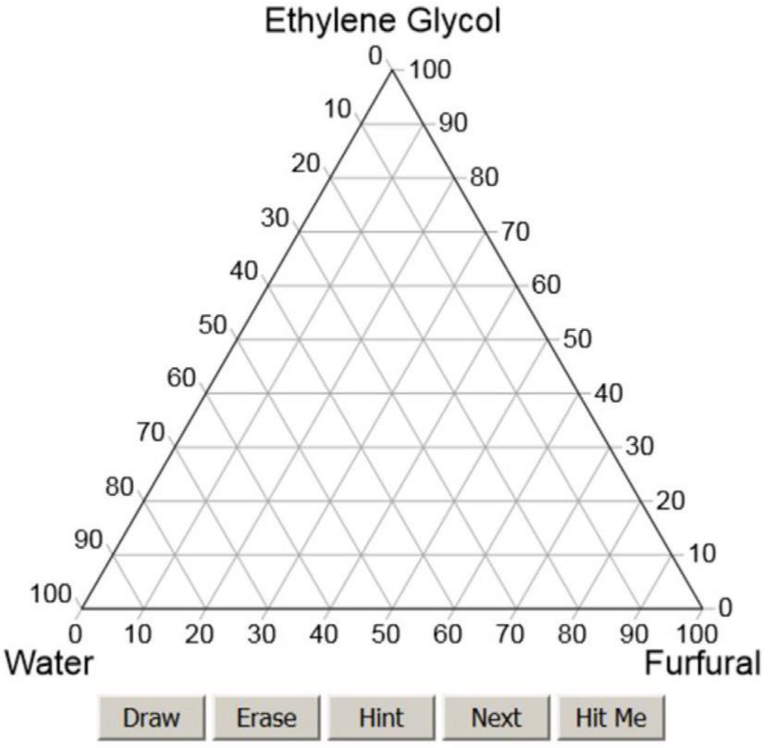
I

Q1: Use the data in the tables provided to draw the liquid-liquid 2-phase boundary on the ternary diagram below.

Hint: The 2-phase boundary is the boundary between the region where the 3 liquids form 2 separate phases at equilibrium.

II

III



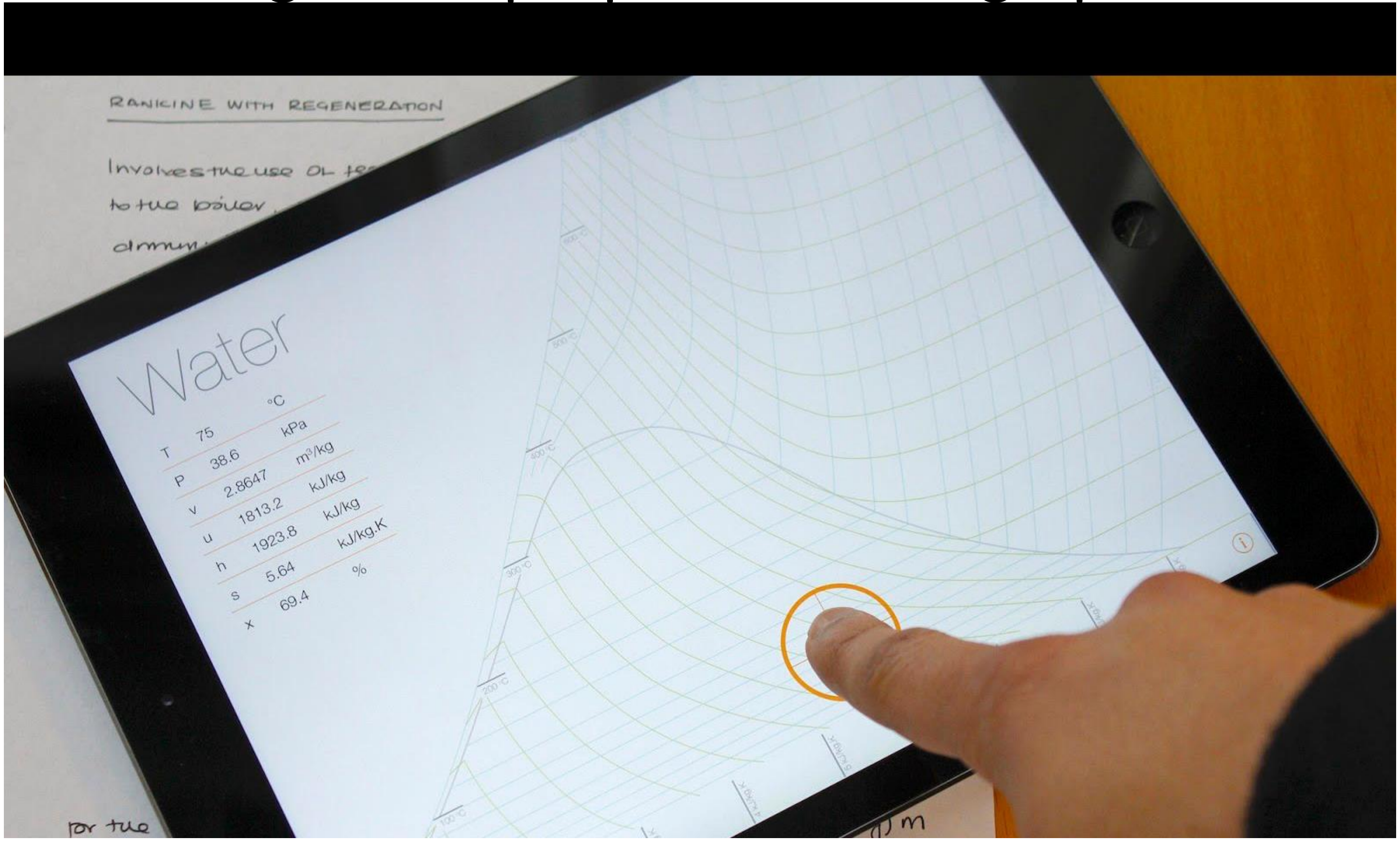
Examples – Use of APPs

- Clausius mobile app previously developed for obtaining water properties from graphical interface
  - Throughout ME thermo course, students obtained all water properties from the app
  - At end of semester, students were significantly better at predicting qualitative cause-effect relationships (e.g., will this cause the entropy to go up or down?) than a control group that used steam tables
  - The property estimates obtained aren't always as precise as from steam tables

S. Bakrania and K. E. Mallouk, "Blowing off Steam Tables", *Proceedings of the ASEE Annual Conference and Exposition*, June 2017.

Examples – Use of APPs

- Bakrania and Mallouck present Clausius mobile app for obtaining water properties from graphs



What is happening in the last year or two in thermodynamics education research?

- 2018 ASEE Conference- Identified dozens of papers with thermodynamics in title or as keyword
  - Many were on topics like diversity, active learning, and group work, that involved a thermo course but could have been implemented in most any course

- Of the papers that really were specific to <u>thermodynamics</u> instruction:
  - Over half were published in the Mechanical Engineering Division. Materials Science also well represented.
  - Most concerned implementation of a specific lab, simulation exercise, or course module in a course

Inquiry-Based Activities

- Used to correct student misconceptions
  - Rate vs. amount
  - Radiation
- Assessment used Heat and Energy Concept Inventory
- Computer simulations and physical experiments both led to improvement, but physical experiments had a bigger effect
- No gender differences observed

Nottis, et al., "Computer Simulations vs. Physical Experiments: A Gender Comparison of Implementation Methods for Inquiry-Based Heat Transfer Activities," *Proceedings of the 2018 ASEE Conference and Exposition,* June 2018.

Position Paper on Government Policy

- Students in a junior level ME Thermo course write one-page position memo on a contemporary governmental policy related to mechanical engineering
- Assignment used to assess ABET-h ("…understand the impact of engineering solutions in a global, economic, environmental, and societal context")
- The development of a detailed rubric for the assignment led directly to improved student performance

K. Gosselin and N. Okamoto, "Improving Instruction and Assessment via Bloom's Taxonomy and Descriptive Rubrics," *Proceedings of the 2018 ASEE Conference and Exposition,* June 2018.

Growth Mindset

"… Someone with a fixed mindset believes that their intelligence is fixed and unchangeable. On the other hand, someone with a growth mindset believes that their intelligence is changeable and can grow as they learn more…"

"If students have a fixed mindset, they may be at a disadvantage coming into a class that they think is going to be especially difficult because they don't think that their hard work will help them succeed. In contrast, students with a growth mindset might appreciate the learning opportunities that a well-structured but difficult class offers."

M. Frary, "Encouraging a Growth Mindset in Engineering Students," *Proceedings of the 2018 ASEE Conference and Exposition,* June 2018.

Other Example Titles from 2018 ASEE Conference

- “An Experiential Learning Exercise: Optimization of Evaporators and Condensers in a Vapor Compression Cycle” (*Zietlow and Sullivan*)
- “Assessment of Fluid Power Modules Embedded in Junior Level Thermodynamics and Fluid Mechanics Courses” (*Liu et al.*)
- “Implementing Collaborative Projects Using a National Academy of Engineering (NAE) Grand Challenge: Provide Access to Clean Water” (*Wright, Milanovic and Eppes*)
- “Undergraduate Freshman Developing Advanced Research Project: Learn-by-Discovery Module to Investigate Energy Efficiency and Energy Conservation Principles” (*Husanu et al*.)
- “Integrated Learning In Context for Heat Exchanger Analysis” (*Lugowski and Hutzel*)

In light of what was presented, what's next?

- *"…we encourage physical chemistry education researchers and practitioners to collaborate across disciplinary lines with mathematicians, physicists, and engineers who also seek to help students understanding the challenging topics in thermodynamics."*

--Marcy Towns et al., 2014

- *"…we see little evidence that the [concept] research is drawing across disciplinary boundaries to make progress in this arena....The greatest progress in our goals will be made by coordinating resources, focusing on how students understand ideas within thermodynamics, and talking across disciplinary boundaries."*

-- Benjamin Geller et al., 2015