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Thermo for Keeps

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Sean Sloan began as a 3.5/5.0 rated professor teaching thermodynamics 15 years ago. After applying changes to delivery including demos and scaffolding, ratings are now 4.8-5.0/5. With graduate background in mechanical engineering, nuclear engineering and education, and work experience managing Naval Reactors thermal-hydraulic research, Sean uses relevant work examples to reinforce concepts. Sean now teaches thermal-fluid sciences at Oregon Tech in their Mechanical Engineering program which includes thermodynamics and CFD.

Thermo for Keeps

Abstract

Thermodynamics is often the most hated course in the mechanical engineering curriculum. Why? Because when you add up all the possible combinations of applied equations, they become overwhelming, with often subtle differences that are hard to remember. To counter this, four key principles become a foundation. If these are well understood, simple math operations on these may create the rest. These principles are: 1. $Q = mC\Delta T$, 2. Understanding latent heat, 3. Understanding $P\Delta V$ work, and 4. Law of the Turbine (an artifice for student discussion establishing constant entropy across a turbine, in a piston, etc). Even the confusing difference between Internal Energy and Enthalpy can be relegated to a combination of #1 and #3. Teachers of thermodynamics should expect to see a significant increase in retention by first investing in these 4 principles. A method that uses percentages to teach interpolation is also discussed. Turning plug-and-chug engineers into conceptual engineers can be difficult, but the investment pays dividends.

Introduction:

For those of you who have attempted to teach thermodynamics, allow me to share with you some ideas that have worked for me and many of my students. Over a 15 year period, student evaluations have raised from 3.3/5 to 4.9/5. Furthermore, test score averages have risen from 76% to 86% creating a bi-modal distribution where half of the class masters the material with "A"s, yet 5-15% of each class still end up with "D"s and "F"s. The most significant change I implemented over this time period is refocusing away from equation memorization and towards understanding concepts. Specifically addressed are the concepts that establish a foundation. These are sensible heat, latent heat, why we differentiate between U, internal energy and H, enthalpy, and how do we cross turbines when we can only define 3 of the 4 pieces of information needed to nail down the energy levels before and after. Once these are well understood, the rest of thermodynamics seems to take half the time to learn (opinion). However, skipping one, creates an untenable position that forces students to get by on memorizing equations and hoping they choose the right one.

Teaching in general

Quizzes:

One method that has increased student aptitude across all genres of classes – weekly quizzes. Every Monday, students take a 5-minute quiz. Why Monday? I am still rusty from the weekend and need a few minutes to center and focus on how I am delivering my lesson plan and lets me see what has stuck and what they missed. Why 5-minutes? It is enough to see how they are following the gist of the previous week and allows time to revise the lesson. I thought this was the end of this evolution, but I found something better.

I originally graded the quizzes during the week and returned them. Then one term when I was overloaded, I took a shortcut and allowed the students to exchange quizzes with their neighbors to be graded. This immediate feedback to the students leads to more focused questions by the students during the lesson and later, exam scores improved (overall effect of all of the changes used in this paper raised exam scores from 76% to 86%). This experimentation seemed to be working, so I got cocky and decided to let students grade their own quizzes. This provided the same feedback and saved class time (I would post the answers mid quiz). Additionally, I reduced the quiz credit from 10% of the class grade to 0%. Students just want to know where they stand and what do they need to focus on. This removal of all impact may have stopped the good students from studying before the quiz – but gave a more honest assessment of what the students really knew. Now all my classes have Monday quizzes with no observed impact from when the quizzes were graded. (No clear, quantitative data is available to support this claim, however). The low-impact nature of the quizzes remains unclear. Further study could be done. It is my opinion that this not only focuses the student on what is important, but also facilitates getting to additional and more attuned instructional time. I suggest trying this in your classroom and deciding for yourselves.

Equation, Substitution, Calculation, Units (ESCU):

From the first day ESCU is introduced to the class as the method to break down problem solving and also used in grading. In solving problems, this method helps identify the governing physics and then identifies which variables are unknown to give the student an avenue to investigate. Roughly the credit value given is 30-30-30-10.

Equations define the physics and if they cannot determine this, all the rest is irrelevant. Watching the teacher put an equation down and solve it won't get them there either. That is why homework is essential to move from observation, to understanding enough to solve problems for themselves.

Substitution separates the plug-and-chug engineers from those that understand the physics. Too many students will substitute in the first variable they see that satisfies the units – regardless of x-y-z directions! Correct substitution shows that they understand what values are relevant.

Calculation shows that the engineers understand math. An engineer that can't do the math is useless.

Units show there is a difference between apples and oranges, but yet somehow fail to discriminate between torque and work…which is why N-m and Joules are not interchangeable in my classes, mostly.

mks units and simple notation:

Notation:

The advantage of turning all problems into meters, kilograms, and seconds is that the units clutter the board. All numbers are written in the substitution step (on the board) without units after them. This is dangerous as it fails to reinforce units. This should only be done after assessments indicate a firm grasp on units.

Simple notation means trying to demonstrate concepts using round numbers. When teaching how control volumes work; showing a control volume in steady state, where 2 joules of work go in and 3 joules of heat go in makes 5 joules of energy to come out. This allows students to focus on the balance rather than the math where 47 joules of work go in and 58 joules of heat go in. Notice how the less math inclined people are focused on doing the math and not focused on learning how control volumes work. This is not where I want them to be thinking, so I select numbers that can focus their attention to the point I want to make. (105 joules by the way). This simple notation is obviously optional, the point is – be deliberate on what you are teaching at the time, control volumes or math.

Teaching Thermodynamics

Oregon Tech's ENGR 355 Thermodynamics attempts to give students 90% knowledge of the first 6 chapters of <u>Fundamentals of Thermodynamics</u>, Moran et. al. 2024. all within three, 50-minute instructional periods per week for 10 weeks and a 2-hour final. These chapters include understanding how to solve problems in saturation, energy calcs with convective energies, enthalpy, internal energy, specific values, control volumes, heat exchangers; Carnot and regular efficiencies of power generation, refrigeration and heat pumps; entropy; reversibility, TdS, isentropic movements using both math and tables, all with being able to determine the amount of heat or work passed in a device.

Pre-requisite knowledge:

The course has minimum pre-requisites of Calculus II and Physics II (where heat is introduced). Although chemistry is not listed, most students take chemistry before physics and the material introduced in physics is adequate to succeed in thermodynamics – although a reinforcement from chemistry is beneficial.

Underlying principles (precursor):

Before I delve into the four major ideas from which the rest is built on, allow me to offer a major deviation from convention. Current practice dictates that in a control volume heat **entering** a control volume is positive but work **leaving** a control volume is positive. Power plant engineers did not want to be sending out negative work and they set the convention of work leaving the control volume is defined as positive, so conservation of energy had to be defined as $\Delta E = Q - W$ …there it is. However, conservation of energy does not care of the mode that a joule is transporting, heat or work. It is unintuitive that heat and work should be treated oppositely in sign. So, in their book, <u>Fundamentals of Engineering Thermodynamics</u>, Howell and Buckius

,1987, work joules **entering** a control volume were defined as positive (just like heat). This change in sign convention created a more intuitive conservation of energy equation: $\Delta E = Q + W$.

For the students, introducing this deviation from modern convention brings up a quagmire. However, Kohler determined that controversies are more interesting and focuses on learning. By teaching both the world's convention, Moran 2024, $\Delta E = Q - W$, and Howell and Buckius' 1987, convention, $\Delta E = Q + W$; the issue helps focus students on why they are different in order to move on – this helps them process control volumes in a real way and student retention dramatically increases. To avoid uncertainty in assessments, real-life problems are used such as a power plant takes in 12kW of heat from coal and expels 4kW of heat to the river. How much work rate is produced? Either convention yields the same answer, 8kW (perhaps -8kW if you are with Howell and Buckius, 1987, but either way, it is power leaving the control volume).

I encourage the reader to reflect on the student question after they are tested, "Why are work joules treated differently than heat joules?" This method, by making an issue of it, creates an enduring understanding of why the "-" sign on work, and even though it takes more time initially, prevents confusion and later reteaching. In my fall '24 class, 75% of the 36 students wanted to use the world's convention initially. Within a week, all but one converted to the Howell and Buckius method. During testing, most errors on energy accounting come from not understanding the sign convention on work and not drawing an appropriate control volume. I recommend eliminating unnecessary and confusing conventions and let students focus on joule movement. But to live in this world both conventions need to be addressed and understood – or just stick to Moran's, 2024, conventional approach. But be sure to tell students why work joules are different than heat joules.

The four Foundations of Thermodynamics:

Students want to be plug and chug engineers. This leads to dangerous application of joules moving in the wrong direction. By moving students away from mindless application of equations, and towards understanding the underlaying principles of those equations, students more readily understand what is going on, and enduring understandings are created and maintained. The four critical understandings that allow the rest of thermodynamics to be learned are:

1. $Q = mC\Delta T$,
2. Understanding latent heat,
3. Understanding $P\Delta V$ work, and
4. Law of the turbine.

Mapping:

The below mapping shows how each of the 4 concepts help to establish connections to the concept taught in Thermodynamics I: The topics addressed beyond the four above are phase diagrams (1,2), ideal gas law (3), determining energy levels(1,2,3), use of energy levels(1,2,3), internal energy(1,2,3), enthalpy(1,2,3), energy accounting (control volumes) (1,2,3), use of entropy(4), $\Delta E=Q\pm W$ (Conventional or Howell and Buckius') (1,2,3), heat exchangers(1,2,3), using U or H(1,2,3,4), and using Cp or Cv(1,2,3,4). What remains largely unaddressed through the above four concepts are interpolation(none), cycles(none), and Carnot cycles(none). Further these above four concepts provide an excellent basis for chapters 8-14 in Moran, for Thermodynamics II. These include: Rankine(1,2,3,4), Otto(1,2,3,4), Diesel(1,2,3,4), and Dual(1,2,3,4) cycles with refrigeration in Rankine and Brayton(1,2,3,4); isentropic math models (Pv^k)(3,4), isentropic air (k=1.4) tables(3,4), un-ideal compressibility(none), combustion(1,2,3), and adiabatic flame temperature(1,2,3).

1. Sensible heat, $Q = mC\Delta T$:

I am constantly amazed how little physics emphasizes this and students leave physics II with poor understanding of sensible heat. They understand when you put a pot of water on the stove and heat it…it warms up. This example grounds $Q = mC\Delta T$ and is the fundamental way that heat interacts with solids and liquids. If students do not grasp this, it is impossible to describe other methods of how heat interacts with matter. Using extra time to teach this and assess it, is vital to moving on. If you lose 10% here, you will never get them back. Also be sure to overtly differentiate between heat, Q and Temperature, T. Many that make it through physics II, still make the mistake that Q and T are the same.

2. Latent heat, $Q=mL$:

That pot of water on the stove, once it reaches 100 ºC, all the water does not immediately evaporate. It truly is like watching water boil and takes a lot of heat to finish the job. Understanding this boiling process leads to the saturation curve and quality (how much is boiled off). I encourage drawing a heat (x-axis) vs. Temperature (y-axis) graph for water; using a C of 0.5 cal/g ºC from 0K to 273K, L = 80 cal/g from solid to liquid, C=1 cal/g ºC from 273K to 373K, and L = 540 cal/g from liquid to gas. Voila, there is more heat exchanged in the water from liquid to gas than to bring it from absolute 0 to boiling. Steam burns hurt! This not only shows the difference between sensible and latent heat, but also introduces the concept of heat content which is used in determining the power moved in a device, like out of a turbine.

Once latent heat and energy level is understood, other concepts like what is "hotter" a cup of coffee or an iceberg may be made (difference between specific heat and total heat). Another is generating a Pressure-Volume saturation curve for water and show (with tables) how pressure and temperature in saturation are linked. Use tables and graphs to help the students understand the base equations more than plug and chug.

3. Understanding PΔV work:

What is the difference between internal energy U, and enthalpy, H? Many students are confused as to why we look at energy levels with 2 different meters. Almost none come out of physics II understanding the concept of PΔV work. I recommend teaching this with a control volume moving gas through a pipe with a pressure difference across it through an area, A and moving a distance, d. Force x distance work is then easily related to ΔP x A x d work. Then, too, it can be shown as expanding a Δvolume through a P → PΔV work. But students had trouble remembering this concept until I included a fire piston demo to the lesson as shown in figure 1. When loaded with some cotton or tissue paper, compressing the plunger imparts work to the contained gas through a ΔV. These PΔV work joules must go somewhere – into the gas. This ignites the paper (218 ºC to 246 ºC). Wow, fire! I then put the fire piston in a visible place in the classroom and point to it whenever I refer to PΔV work (a definite phenomenon is established that is marked and easily pointed out as it occurs in problems). I also show how a can of air cools off when the air inside (small V) is released to the classroom (big V) and it becomes too cold to touch because it lost all those joules to making the gas expand – pushing against the environment with PΔV work, making the volume bigger. Putting a baggie around the exhaust emphasizes the ΔV. Having a physical representation of PΔV work allows the students to hang their understanding on a more concrete thing and remember it better.

Now that they know PΔV work. Gases must accommodate the PΔV in addition to increasing temperature. This leads to $\Delta H = \Delta U + P\Delta V$ the difference between enthalpy and internal energy. Or $\mathbf{mC_p\Delta T} = \mathbf{mC_v\Delta T} + P\Delta V$ if you prefer relating it back to sensible heat. One student described it brilliantly, "You have to pay the PΔV tax too if you let the gas grow". If you ignore all the rest of this paper and want to include the most useful piece of advice, get a fire piston. It demystifies enthalpy and internal energy.

Figure 1: acrylic fire piston compliments of

https://www.homesciencetools.com/product/fire-syringe-demonstrator/

4. Law of the turbine:

There is no law of the turbine, I made it up. You see, students had a hard time remembering the convention that entropy, S, is the same before and after the process of a turbine, nozzle, pump or piston. Without the convention, it is impossible to calculate the expected P, V, T relation from before the device to afterwards. Too many students left these assessment questions blank. Somehow students remember laws better than conventions – so I called it a law. It also made it more succinct referring to it during lessons. Students could remember it! So, if you want me to put me in jail for abusing the word, “law”, I am guilty. At least I will go to prison knowing my student can do it. Adopt this if you want, or not, probably depending on if you are more of a pragmatist than a purist. Perhaps this is also the difference between an engineer and a scientist? However, the improvement in student performance is drastic.

Once the law of the turbine is established, the methods of using cold-air-standard math, PV^k, or tables are taught with a few examples from turbines and pistons.

Entropy:

Finally, I do not bother to spend much time on defining entropy, exactly. Entropy is primarily useful in determining the states before and after an isentropic process. I do hit on probability a bit to help for some understanding of why entropy matters in thermodynamics. If 1 mole is 6.02×10^{23}, and a Becker bottle contains 1,000,000 beads in it (1M), and 22.4 liters of air at STP (mole) would contain the same number of molecules as 1M Becker bottles per train car, 1M train cars per train and 602k trains – which would cover 1/10th the surface area of the world. Since gases are made up of so many molecules, they will behave statistically predictably. The best definition I have for entropy is it measures the lost work you could have had with a temperature difference of you mix the gases instead of putting them through a Carnot power cycle.

https://www.flinnsci.com/becker-bottle-one-in-a-million

Conclusion

For teaching and learning thermodynamics, make sure the basics are nailed down before moving on. Make sure the governing equations are well understood and the physics behind the equations are well understood. These foundations are described as:

1. $Q = mC\Delta T$,
2. Understanding latent heat,
3. Understanding $P\Delta V$ work, and
4. Law of the turbine.

Moving slower through these at first allows for a firm foundation that without would cause confusion. Knowing the basics well allows the more complex to be understood and creates an enduring understanding. This, in turn, allows more rapid progression later and more overall knowledge imparted over the course of a 10-week class. This gives the student a better understanding of thermodynamics that they can keep.

Appendix I

Interpolation:

A colleague was having difficulties remembering an interpolation formula, so he used linear mapping to recreate it. This made me realize that most engineers do this because it is easier to remember. So, this is now how I teach it. Instead of formulae, I paint the picture with a race and percentage through the race. That way, to determine enthalpy in saturation, the enthalpy at a quality of 60% is equal to 60% of the way from start enthalpy (sat. liquid) to the finish line (sat. gas). The one formula then that replaces all other interpolations is:

% = distance into the race / length of the race. This maps directly to Moran's equations like:

X = {h-h(liquid)} / {h(gas)-h(liquid)}.

When solving algebraically for h this becomes:

position = start + X (race)

or

h = **h(liquid) + X {h(gas)-h(liquid)}**

Turn all linear interpolations into a race by calculating what percentage you are through the race. Remembering three items (X, distance, race) is much easier then remembering the order of the 5 items as presented in most books.

Bibliography:

Fundamentals of Thermodynamics, Moran, et al. 9th edition, Wiley publishing, 2024.

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