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2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #49275

Pressure-enthalpy diagram centric approach to open-system component, Brayton cycle, and Rankine cycle analysis in a thermodynamics course

Cmdr. Matthew Schell, United States Naval Academy

Commander Matt Schell is a Navy Reservist currently recalled to active duty as a Master Instructor in the Mechanical and Nuclear Engineering Department at the United States Naval Academy. He started his Navy career on active duty as a nuclear-trained submarine officer. As a civilian, he worked for ten years at the Navy Nuclear Lab in the Pittsburgh Area. At Navy Nuclear Lab he had cognizance over various aspects of the Navy Nuclear Power Training Pipeline and then became an instructor in the Bettis Reactor Engineering School. Matt earned a B.S. and M.S. in Physics from the University of Pittsburgh (1997 & 1999).

Prof. Andrew N Smith, United States Naval Academy

Pressure-Enthalpy Diagram Centric Approach to Open-System Component, Brayton Cycle, and Rankine Cycle Analysis in a Thermodynamics Course

Abstract

This paper presents a graphical approach to teaching thermodynamic open-system component analysis, steam cycle analysis, and gas turbine analysis centered around the pressure-enthalpy (p-h) diagram. Our approach, inspired by Israel Ureli's p-h diagram analysis of basic steam cycles, extends p-h diagram analysis to entire steam cycles including throttle valves and steam turbine adiabatic efficiency. Additionally, we present a pedagogical approach to gas turbine engine analysis through the introduction of a p-h diagram developed for air. To our knowledge, our further extension of the p-h diagram approach to quantitative gas turbine analysis in a classroom environment is new in engineering pedagogy. We find that the p-h diagram approach is more digestible to students and allows for a deeper understanding of the limitations imposed by the first and second laws of thermodynamics.

The p-h diagram approach was implemented in a thermodynamics sequence with a large number of students and multiple instructors. Along with instructor surveys, data is presented based on final exam performance that highlights the value of a graphical approach.

Background - Graphical Approaches to Thermodynamics

Introductory engineering thermodynamics courses typically begin by providing two approaches to finding thermodynamics properties: the ideal gas law and property tables. Although notional illustrations of thermodynamic processes and cycles on pressure-volume and temperature - entropy diagrams are common, obtaining thermodynamic properties graphically is not emphasized. For example,well established texts [1] and [2] use simplified phase diagrams to graphically illustrate and explain cycle analysis, however they only introduce graphical methods to obtain thermodynamic properties when they cover refrigeration cycles late in the text. Even then the majority of the refrigeration examples in these texts still focus on using property tables.

Some educators have advocated for moving away from steam tables entirely [3]. There are also examples of educators implementing interactive graphical demonstrations [4] and simulator-based games [5] to teach property relations. Smitesh Bakrina strongly advocates for a visual approach to teaching the properties of water [6] and has published graphical resources and videos that help students learn about property relations [7]. Israel Urieli extended the graphical approach to cycle analysis in [8] and [9]. Urieli promotes the use of graphical methods for the quantitative analysis of steam and refrigeration cycles using the semilog pressure-specific enthalpy (p-h) diagram.

Graphical approaches to quantitative gas turbine analysis are uncommon although resources that qualitatively illustrate the Brayton cycle on a p-h diagram can be found online [10] and [11]. Typically educators use the ideal gas law and constant specific heats to build a fundamental understanding of the property relations, and then introduce air tables for increased accuracy. However, as shown in this paper, a p-h diagram centric graphical approach can be used for quantitative gas turbine analysis.

Background - Cycle Analysis Cognitive Challenges

Common open-system applications in introductory engineering thermodynamics include nozzles, diffusers, turbines, compressors, heat exchange processes, and valves. After analyzing open-system components in isolation, they are combined to model gas turbines, steam power plants, and refrigeration plants using the Brayton cycle, Rankine cycle, and refrigeration cycle with some modifications to account for departures from the idealized model. Students are challenged by cycle analysis since they must remain mindful of three new concepts simultaneously:

- the purpose of the component being analyzed (e.g., a nozzle converts enthalpy to kinetic energy),
- the engineering model being applied to that component (e.g., reversible and adiabatic),
- and the procedure for analyzing working fluid properties (e.g., air table procedures, ideal gas isentropic process relationships, or steam table procedures).

Viewed through the lens of cognitive load theory [12], each of these three concepts represents a new "schema" that students must develop and integrate into long term memory. Until each of these schemas are established, students experience a "split attention" penalty and potential cognitive overloads as they shift contexts and reload their working memories while progressing through each aspect of thermodynamic cycle analysis. The challenges of split attention and cognitive overload are particularly acute in single-semester thermodynamics courses where cycles are covered but the time to cover thermodynamic theory and properties is more limited.

Previous work applying applying cognitive load theory to STEM problem solving, for example [13] and [14], provide best practices for STEM pedagogy:

- Keep diagrams, charts, and explanations on the same page to help students focus and avoid split attention [13].
- Use visual cues and signals when content is complex [13].
- If working memory capacity is exceeded while processing information, then some, if not all, of the information will be lost [14].
- Locating all information together reduces the impact of split attention and improves problem solving performance [14].

The juggling required by the equation and table based approaches to introducing thermodynamic cycles runs contrary to these best practices.

In subsequent sections of the paper, we present a pedagogical approach to open-system component, gas turbine, steam plant, and refrigeration plant analysis centered around the p-h diagram that requires less juggling and reduces the split attention penalty associated with thermodynamic cycle analysis. This approach was inspired by the extension of p-h diagram analysis from refrigeration cycles to steam cycles presented in [8] and [9].

Why Select the p-h Diagram?

An important feature of our approach is the use of a single diagram for both thermodynamic property look-ups and process/cycle visualization. In selecting a diagram, one of the axes should be enthalpy so that the energy transfer in a component is visualized as a horizontal or vertical separation on the diagram. The logical choice for the other axis is a parameter that is constant or nearly constant through some of the components. So the logical choices for the other axis are entropy and pressure. We selected a semi-log p-h diagram for several reasons:

- The industry-standard for graphical display of refrigerant data, [15], is the semi-log p-h diagram. By using a p-h diagram for gas turbines and steam cycles the instincts developed in one cycle analysis can be transferred to another. This reduces cognitive burden on students and allows them to focus more on advanced cycle analysis.
- The semilog p-h allows for compact visualization of the subcooled liquid region, the vapor dome, and the superheated region on a single diagram. For pedagogical purposes this is an improvement over the Mollier diagram which does not include the subcooled region.
- T-s diagrams which are often used for qualitative steam cycle analysis are not useful in the subcooled region since compressing liquids results in a very small entropy change. As pointed out in [8], the increase in temperature and entropy for non-isentropic pumps is often grossly exaggerated on qualitative T-s diagram illustrations.

The Naval Academy's Introductory Thermodynamic Curriculum

All Naval Academy graduates, regardless of major, are awarded a Bachelor of Science degree upon graduation. This justification for a Bachelor of Science degree is that all students complete a "core" curriculum that includes three semesters of calculus, a fourth math course, two semesters of chemistry, two semesters of physics and a series of engineering courses that emphasize fluids, thermodynamics, circuits, controls, cyber science, and maritime technology.

Engineering-majors and non-engineering-majors complete identical calculus, physics, and chemistry coursework prior to their thermodynamics course. However, the non-engineering majors take a more applied version of thermodynamics compared to a typical introductory thermodynamics course. In the non-engineering course, there is less emphasis on developing a theoretical understanding of entropy and more emphasis on cycle analysis.

We have implemented the p-h centric approach for both populations of thermodynamics students. However, the course for non-engineering majors has more students, greater uniformity between instructors, and more standardized final exam questions. As a result the non-engineering major exam performance data is more reliable, and student performance data in this paper comes from that course. We surveyed and interviewed instructors from both courses and we feel confident that the p-h centric approach has been equally effective for engineering and non-engineering majors. Based on the similarity in student backgrounds, course content, and instructor perception we assert that the conclusions of this paper are applicable to any introductory engineering thermodynamics course.

Exemplifying p-h Centric Content

This section provides some example content from our p-h centric thermodynamics courses.

The non-engineering major course only covers closed systems using air as the working fluid. In the closed system section of the course, properties are exclusively determined using the ideal gas law and cold air standard. Students are introduced to ideal gasses undergoing closed system processes and the use of Otto and Diesel cycle models to analyze reciprocating internal combustion engines. In the course for engineering majors, property table look-ups are introduced and used to analyze closed systems early in the course.

In both courses, upon reaching open-systems, the role of enthalpy is emphasized and the p-h diagram for air is introduced. U.S. Customary System (USCS) and Metric System (SI) p-h diagrams were created based on [16]. See Appendix A for blank copies of these tables. Students initially complete a set of drills to look up air properties on the p-h diagram.

One of the first components analyzed with the p-h diagram is a nozzle. Using typical simplifying assumptions (adiabatic and frictionless), a conservation of energy argument is used to show that the reduction in specific enthalpy in a nozzle is equal to the increase in specific kinetic energy. Various nozzle processes are then shown superimposed on a p-h diagram (Figure 1).

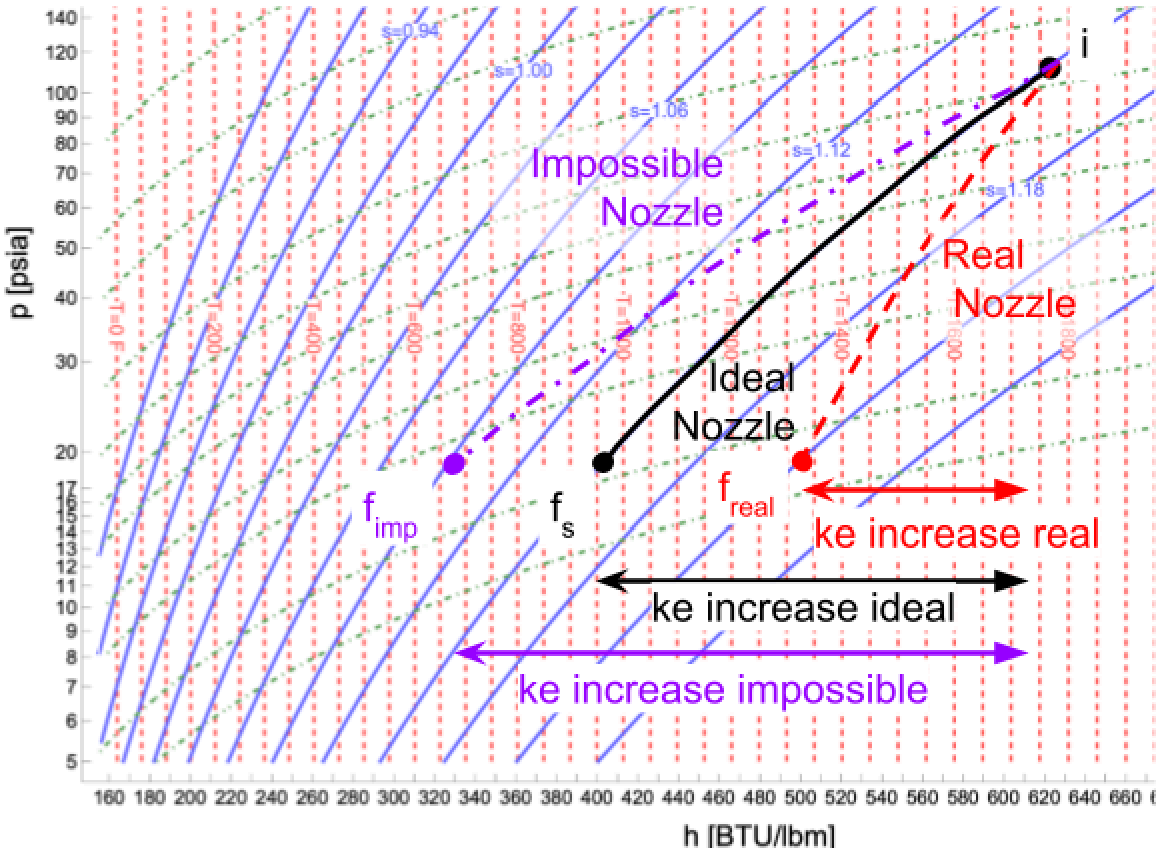

Figure 1. Nozzle Processes on the p-h Diagram

This first example illustrates how the p-h centric approach makes the consequences of the first and second law visual and intuitive. Under typical simplifying assumptions, the horizontal separation on the diagram is proportional to the specific kinetic energy liberated by the nozzle. Students quickly recognize that the most desirable condition would be to maximize the horizontal separation for a given pressure drop. However, the second law clearly limits the allowed horizontal separation for a given pressure drop.

Of course, the same type of argument could be made on a enthalpy-entropy (h-s) diagram *notionally* illustrated in standard textbooks. However, in our approach the intuition about isentropic efficiency is more strongly enforced throughout the course because the students use *the same tool to find thermodynamic properties and analyze thermodynamic processes*. This approach is consistent with the cognitive load theory best practices for STEM problem solving emphasized in [13] and [14].

The air p-h diagram is used to analyze compressors, turbines, and heat transfer processes. A common theme is that under typical simplifying assumptions, the horizontal separation is associated with the relevant energy transfer and that inefficiencies make work inputs larger and work outputs smaller. Similar observations for nozzles and diffusers can be made regarding the change in kinetic energy.

Gas turbines are the first machines analyzed with the p-h diagram. Figure 2 shows the solution to a split-shaft gas turbine problem. Note that the machine schematic, thermodynamic data, calculation of specific heat transfer and work, and visualization of component processes occur entirely on a single piece of paper as recommended by the cognitive load theory best practices in [13] and [14].

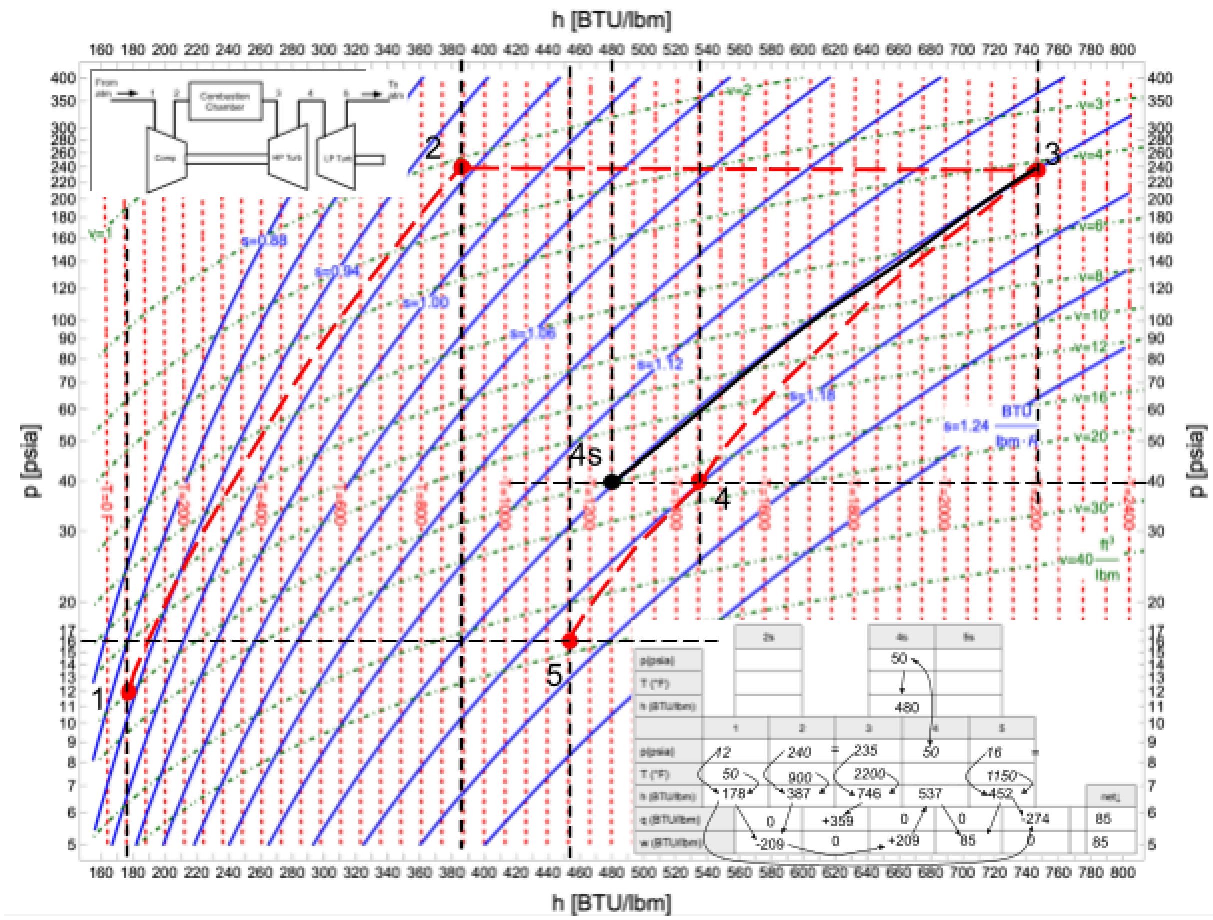

Figure 2. Quantitative Split-Shaft Gas Turbine Analysis on the p-h Diagram

The implications of various qualitative changes on machine performance are visually apparent to students when a p-h diagram approach is used. For example, in the problem above the students can recognize that an ideal high pressure turbine (3 to 4s) would provide more horizontal separation than the real turbine (3 to 4). Similar points could be demonstrated for the compressor and low pressure turbine (however, in the Figure 2 problem T_2 and T_5 were given so the isentropic efficiency of those components was not required).

As another example of qualitative analysis on the p-h diagram, in this problem the head loss in the exhaust ducting causes point 5 to be higher than atmospheric pressure. The higher pressure at point 5 reduces the horizontal separation across the low pressure turbine (4 to 5) and therefore reduces the output power of the machine. The head loss in the intake ducting causes point 1 to be below atmospheric pressure, which clearly increases the work required in the compressor to achieve the same outlet pressure.

Finally, thermal efficiency is visually apparent on the p-h diagram. In the split-shaft gas turbine example, the net work produced is the horizontal separation from 4 to 5, and the heat supplied is the horizontal separation from 2 to 3. Just by looking at Figure 2, students can appreciate that the thermal efficiency is 20%-25% in this problem.

Once students complete gas turbine analysis, we introduce phase changes in the context of the vapor dome illustrated on a p-h diagram. The semi log p-h diagram is ideally suited to demonstrate liquid to vapor transitions. In our course we use p-h diagrams for water (R-718) and R-134a published in [15] by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) and based on [17] for water and [18] for R-134a. ASHRAE has allowed the publication of blank versions of these diagrams in Appendix A, but has not waived any copyright protection or other rights entitled to its intellectual property.

Once students complete drills to look up properties of fluids at or near a saturation, the Rankine cycle is introduced. Our approach to analyzing the steam cycles follows Urieli [9]. As an example of our extension of [9] to additional aspects of steam plant operation, Figure 3 demonstrates the impact of a throttle valve upstream of the turbine. The throttling process is assumed to be isenthalpic. This introduces an additional state point 3.5 before the turbine.

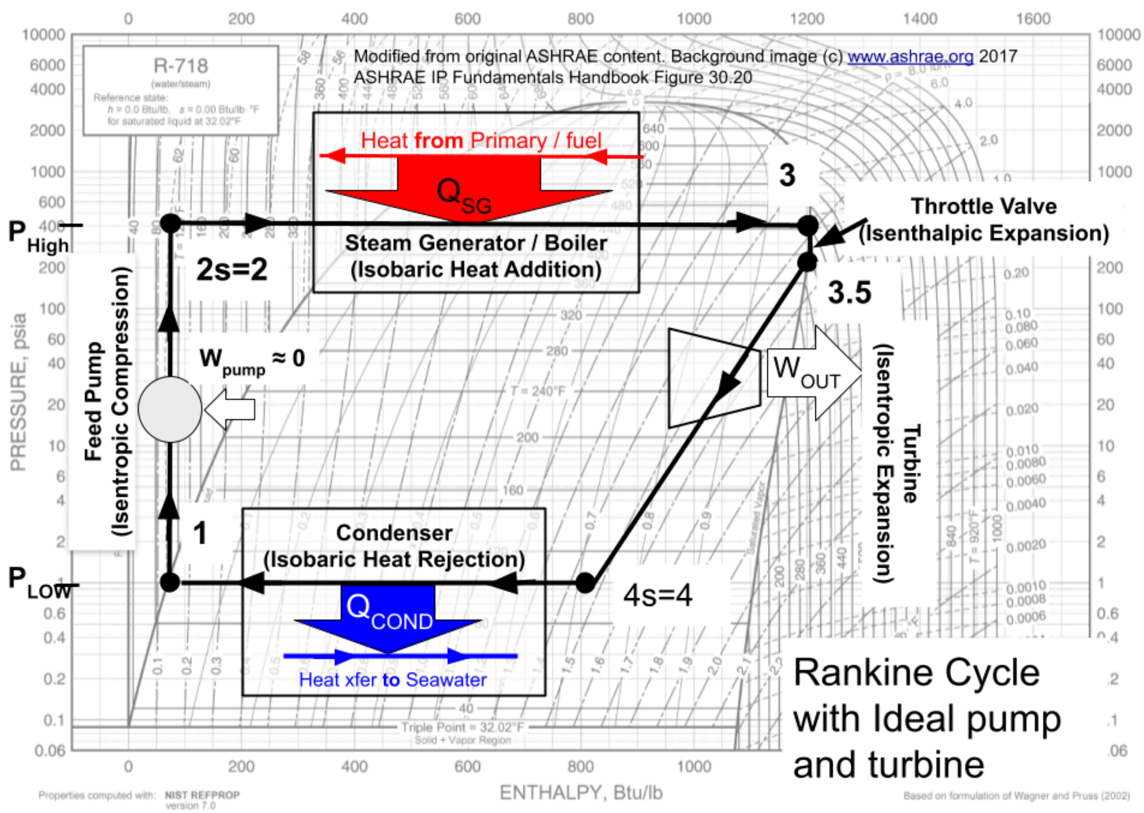

Figure 3. A Steam Cycle with a Throttle Valve on the p-h Diagram

Note that the work of the pump (horizontal separation from 1-2) is nearly indistinguishable on the p-h diagram. While this presents a pedagogical challenge, the same challenge exists when using the thermodynamics property tables. A solution is to calculate the ideal pump work using density and the change in pressure. Density can be obtained from the diagram and is observed to be a near vertical line which reinforces the incompressible liquid assumption and shows when that assumption begins to deviate. Visualizing the pump efficiency is not possible on the p-h diagram for steam cycle problems since the change in entropy is so slight. On the other hand, the indistinguishability of pump work underscores that the compression work in a Rankine cycle is negligible relative to the turbine work and can be juxtaposed with the compressor work in a gas turbine.

Thermal efficiency is also easily visualized in steam cycle problems. Since the compression work is so small, the horizontal separation of the turbine (3.5 to 4) ratioed to the horizontal separation of the steam generator (2 to 3) shows that the thermal efficiency of this highly idealized cycle is roughly 33%.

As advocated by the cognitive load theory best practices in [13] and [14], qualitative analysis of steam cycle performance is visual and intuitive in the p-h diagram approach. For example, condensate depression (subcooling in the condenser) at the pump inlet in Figure 4 results in an obvious increase in horizontal separation across the steam generator with no change in turbine work (3-4) resulting in reduced thermal efficiency.

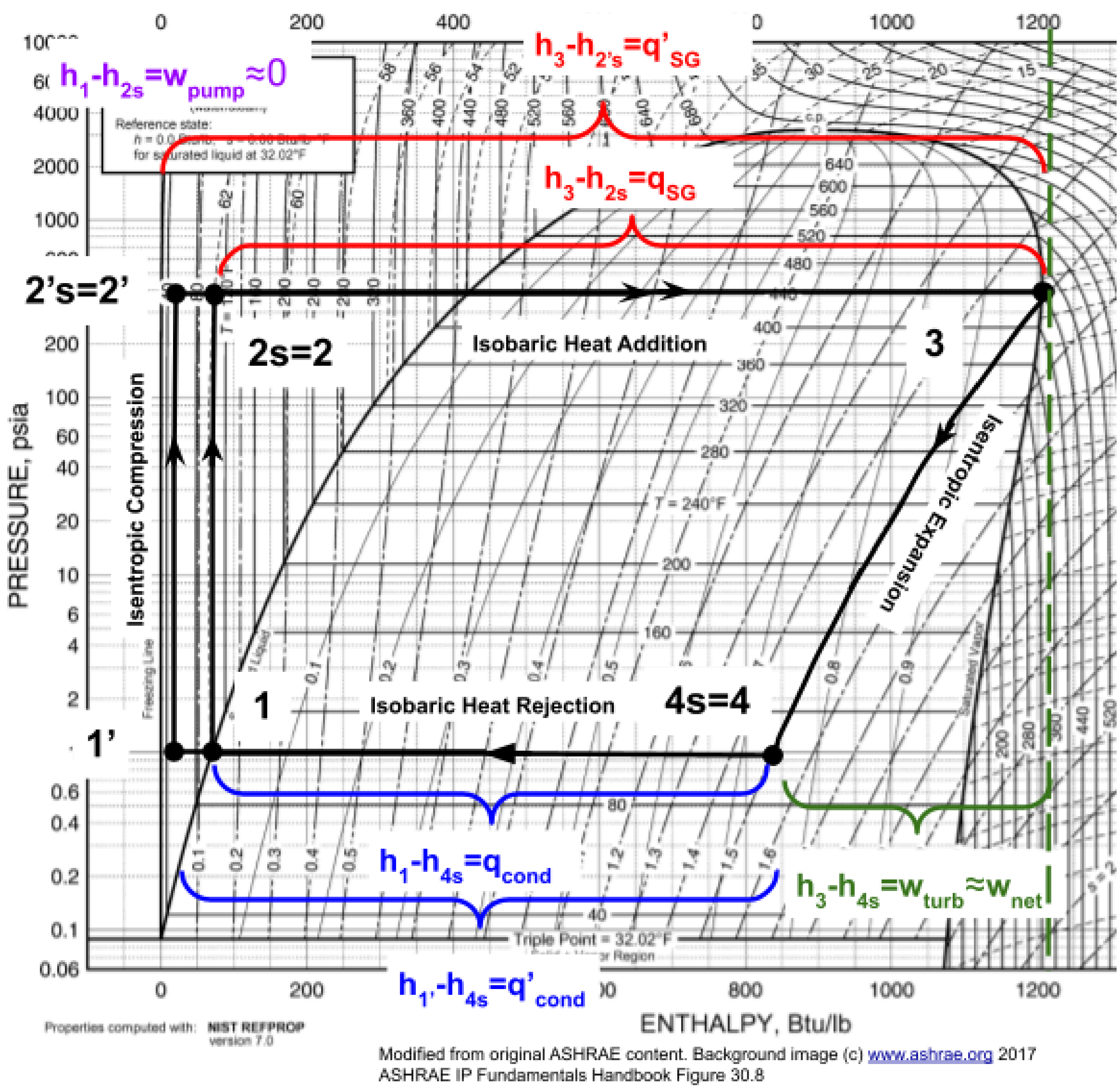

Figure 4. Quantitative Analysis of an Ideal Rankine Cycle on a p-h Diagram

The last cycle analyzed in our courses is refrigeration. We have not presented any of that analysis in this paper since our treatment is fairly standard with a focus on the p-h diagram as the central tool to analyze the cycle.

How did the students perform?

The final exams in our thermodynamics courses are common across all students in a given semester.

Prior to implementing the p-h diagram centric approach, our thermodynamics course for non-engineering majors emphasized using ideal gas equations for gas turbine analysis and steam tables for steam cycle analysis. Mollier diagrams were made available for the turbine portion of the steam cycle analysis but were not required. The table below provides data for the students taking the common final in the legacy course during Academic Year 24 (AY24) to students taking the common final in the revised p-h centric course in fall of AY25.

A perfectly controlled experiment in pedagogy is always challenging. However, our analysis attempted to control as many variables as possible.

- In fall AY25, an effort was made to use conceptually identical questions to previously used final exam questions. Minor changes were made to reflect some nomenclature changes in the course, but the problems were as identical as possible and were graded using a nearly identical rubric. The biggest change was that the legacy steam problem involved superheated steam while the fall AY25 problem involved saturated steam.
- The amount of time spent on each topic, the homework problems assigned, and the resources available to the students were largely unchanged from the legacy course to the revised p-h centric course.
- The pool of instructors was different in the revised p-h centric course, but was drawn from personnel with the same background and experience as is typical for the course.
- Available test time for each problem was nearly identical.

Legacy Course			Revised Course			
Problem	N	Avg Score	Problem	N	Avg Score	p-value
Gas Turbine via Ideal Gas Law	335	65.7%+/- 27.0%	Gas Turbine via p-h diagram	360	80.1% +/- 20.3%	$<10^{-14}$
Steam via steam tables with Mollier option	340	71.4% +/- 23.5%	Steam via p-h diagram	360	91.3% +/- 11.5%	$<10^{-14}$
Refrigeration via p-h diagram	340	75.3%+/- 23.7%	Refrigeration via p-h diagram	360	87.0%+/- 16.7%	$<10^{-12}$

Table 1. Student Final Exam Performance

The data indicate improved student performance on the common final in the p-h centric approach with a high level of statistical significance.

It should be underscored that the legacy approach to refrigeration was identical to the approach in the revised course. The increase in student performance in refrigeration is hypothesized to be due to:

- improved fluency in using the p-h diagram in the gas turbine and steam sections of the course.
- more time to focus on the thermodynamic concepts in the refrigeration section and throughout the course.

In the course for engineering majors, the sample size was smaller and the final exam questions were not as carefully aligned with legacy questions. With those caveats in mind, we report that the fall AY25 instructors in the course for engineering majors reported a significant performance improvement on the cycle questions that used the p-h diagram centric approach.

Our experiment is not perfectly controlled. In a more ideal world, we would have used the same instructor teaching both methods using the same set of problems and assessment questions to a large sample of students in both flavors of our thermodynamics courses. Despite our less than perfect experiment, we conclude that the student performance data suggests that the p-h diagram approach improved understanding.

What did the instructors observe?

In addition to student performance, instructors teaching the p-h centric approach were surveyed. The observations noted below are based on interviews and surveys of twelve instructors teaching the thermodynamics course to non-engineering majors in fall AY25 and four instructors teaching the thermodynamics course to engineering majors in spring of AY24 and fall of AY25.

The instructors provided the following positive feedback on the p-h centric approach:

- Instructors observed that the p-h centric approach reduces the cognitive switching penalty during cycle problems because the working fluid thermodynamic data, thermodynamic process, and component visualization are all located on the same page. In the course for engineering majors, students had the option to use tables or the p-h diagram for the steam and refrigeration problems. Tellingly, in fall AY25 30 of 31 students used the p-h diagram for the steam cycle and 31 of 31 students used the p-h diagram for refrigeration.

- In the p-h centric approach, the correspondence of the horizontal separation to heat, work, or change in kinetic energy improves student intuition about limitations imposed by the first and second laws.
- Student conceptual understanding of isentropic efficiency was improved in the p-h centric approach.
- Steam cycles were substantially easier for students to grasp than the previous steam table based approach.
- Having a common process for analyzing thermodynamic properties that spans gas turbines, steam, and refrigeration allows students to focus more energy on thermodynamic concepts.
- Due to the more concentrated data on the p-h diagram, the p-h centric approach is logistically simpler and allows for more instructor freedom to manage the allowed resources in the exam. In our department, courses with data tables tend to be open notes to varying degrees. The p-h centric approach is more amenable to instructors who desire closed-note assessments.
- Even with a generous tolerance in reading the plot, the p-h diagram is more accurate than the cold air standard ideal gas approach to gas turbines. An air table approach to gas turbines or steam table approach steam cycles is more accurate, but the improved accuracy from the tables is relatively small.

The instructors provided the following concerns about the p-h centric approach:

- The Fundamentals of Engineering (FE) Reference Handbook [19] includes tabulated steam data, tabulated refrigerant data, and p-h diagrams for refrigerant. Although air tables are not part of the Handbook, thermodynamic analysis of ideal gases is included on the FE exam. In our engineering version of the course instructors teach a combination of ideal gas equations, table lookups, and p-h centric graphical analysis. For engineering majors, it is likely worthwhile to continue to have some exposure to tabulated thermodynamic data for steam/refrigerant in support of FE exam preparation.
- A concern related to a "mixed" approach that introduces both the p-h diagram and tabulated data for refrigerants is that there are competing reference states in the literature. For example, the R-134a reference states used in [1] are different from the reference states used in [2] for both the SI and USCS tables. There is internal inconsistency between the reference state in the SI refrigerant table and p-h diagram in [2]. Both using a non-industry standard diagram and using tables that differ from established text have drawbacks. In our department, we have chosen to live with the difference and use the fact that only enthalpy *differences* are physically significant as a teaching point.

Recommendations and Future Work

Using a p-h centric approach for the analysis of open system components, gas turbines, steam cycles, and refrigeration cycles showed significantly improved student performance in the first full semester of implementation. Additionally, instructors had mostly positive feedback on the change. We recommend instructors teaching introductory engineering thermodynamics consider adopting a p-h centric approach. We encourage textbook authors to implement p-h diagrams in the sections on gas power cycles and vapor compression cycles.

The p-h diagram centric approach in the classroom could be especially complementary to courses using electronic thermodynamic programs like Engineering Education Solver (EES). The student can run a preliminary analysis on the p-h diagram and then a more precise analysis in EES.

At our institution, we are considering analogous approaches to reciprocating internal combustion engine analysis. The logical extension of p-h to closed system analysis would be a pressure-specific internal (p-u) energy diagram. One conceptual challenge is that the horizontal separation during the isobaric heat addition in the diesel cycle is not associated with work or heat individually. Nevertheless, we are exploring graphical data lookups in conjunction with Otto and Diesel cycle analysis. For example, we are considering providing the students with graphical pressure-specific volume (p-v) and temperature-specific entropy (T-s) diagrams for air so that the thermodynamic look up and cycle visualization are on the same page.

Another area for future work is developing SI unit tables or diagrams for refrigerants that use a common reference state. In an ideal world a consensus reference point for refrigerants would be established for use across engineering pedagogy.

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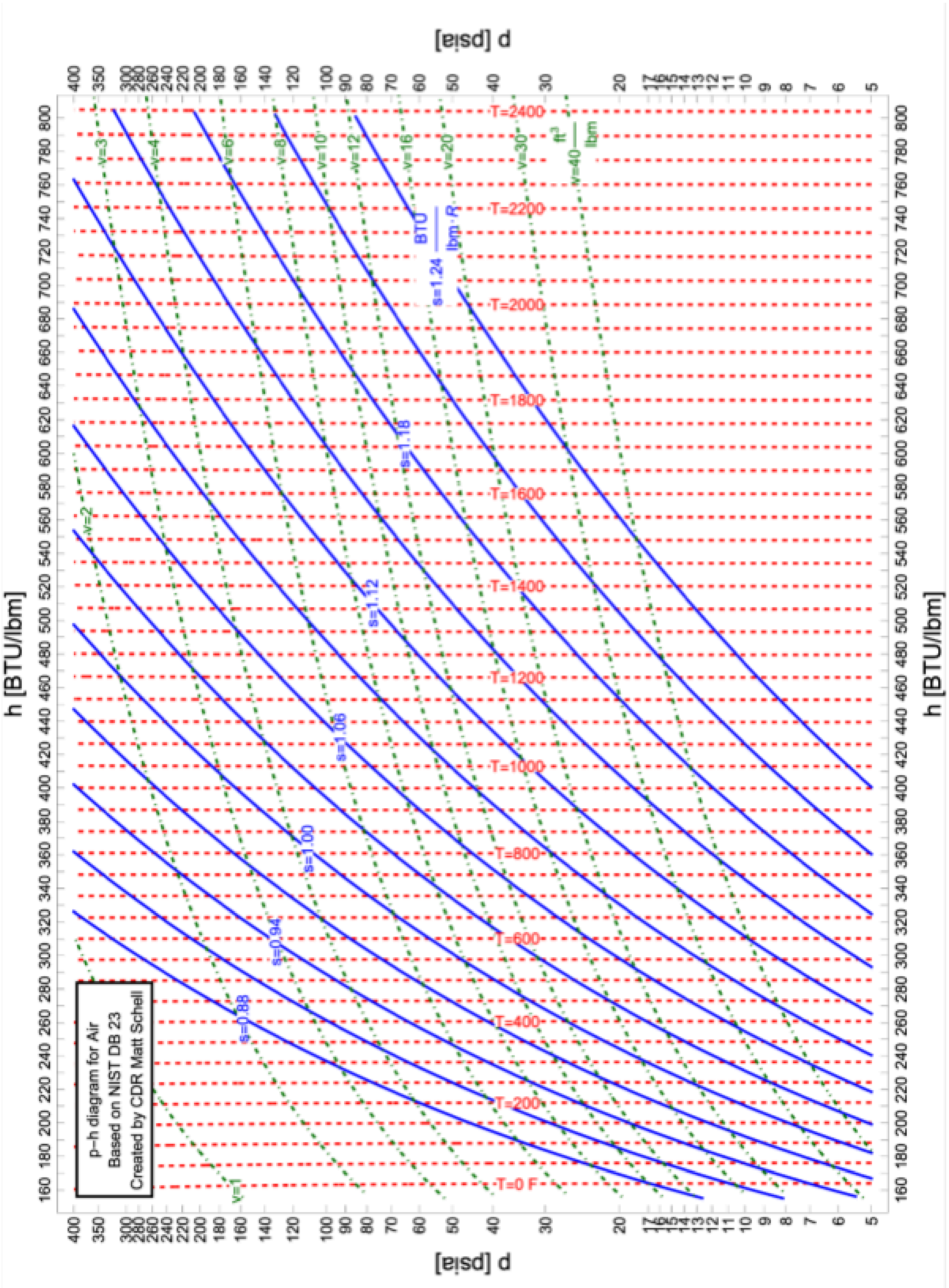
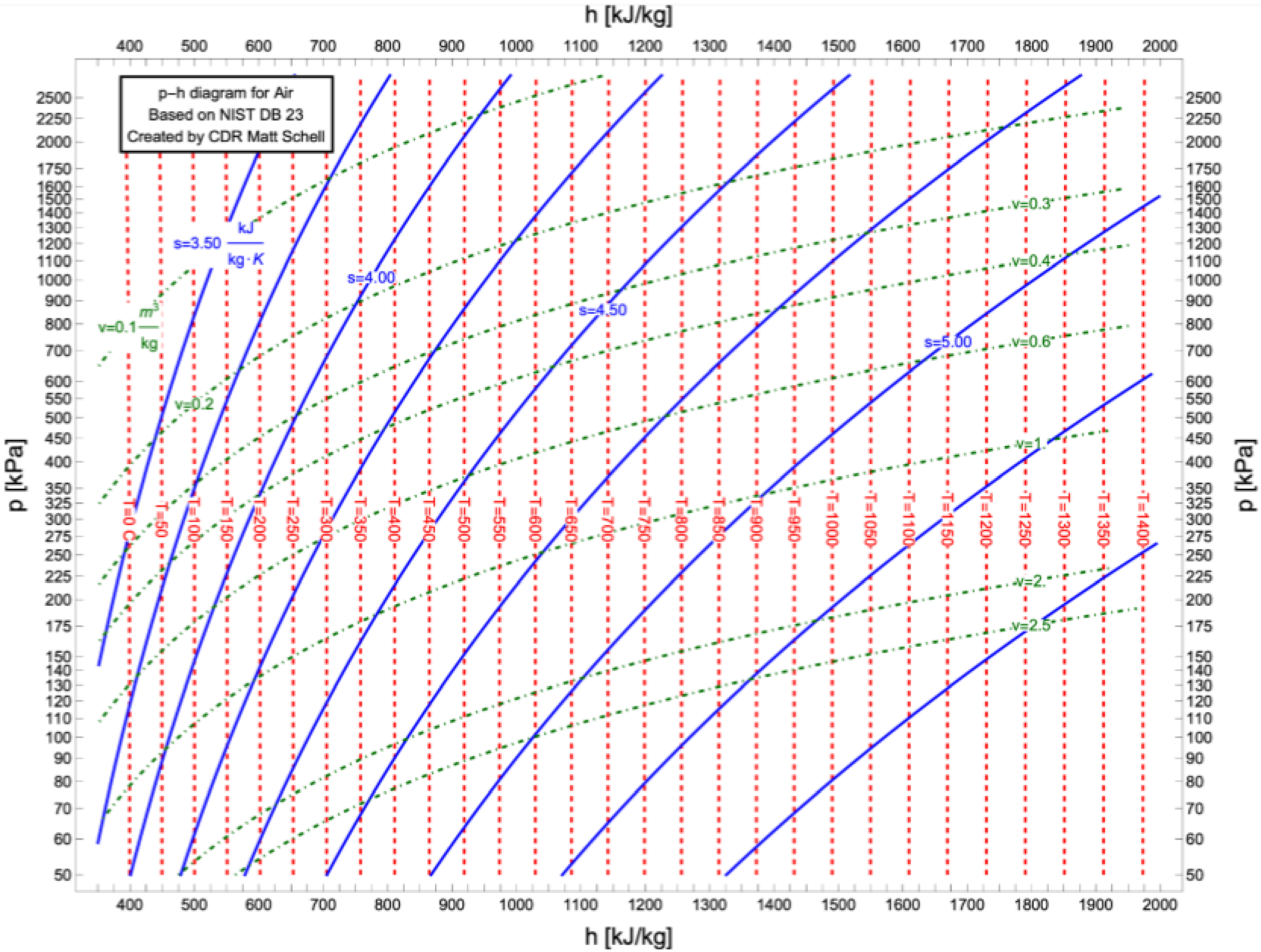
Appendix A: USCS and SI p-h Diagrams for Air, R-134A, and R-718 (water)





p–h diagram for Air
Based on NIST DB 23
Created by CDR Matt Schell
h [kJ/kg]
p [kPa]
s=3.50 kJ/(kg·K)
s=4.00
s=4.50
s=5.00
v=0.1 m³/kg
v=0.2
v=0.3
v=0.4
v=0.6
v=1
v=2
v=2.5
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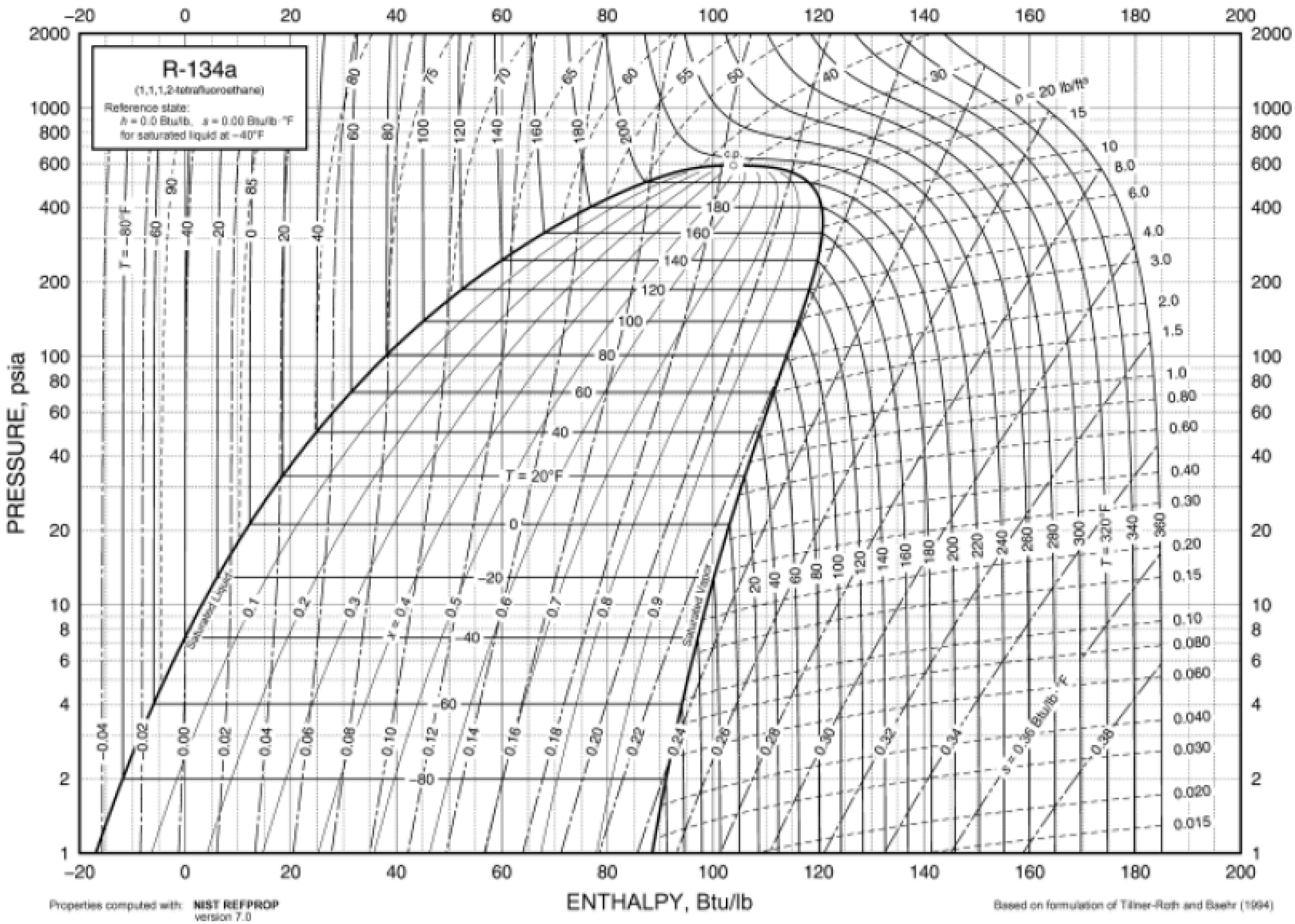
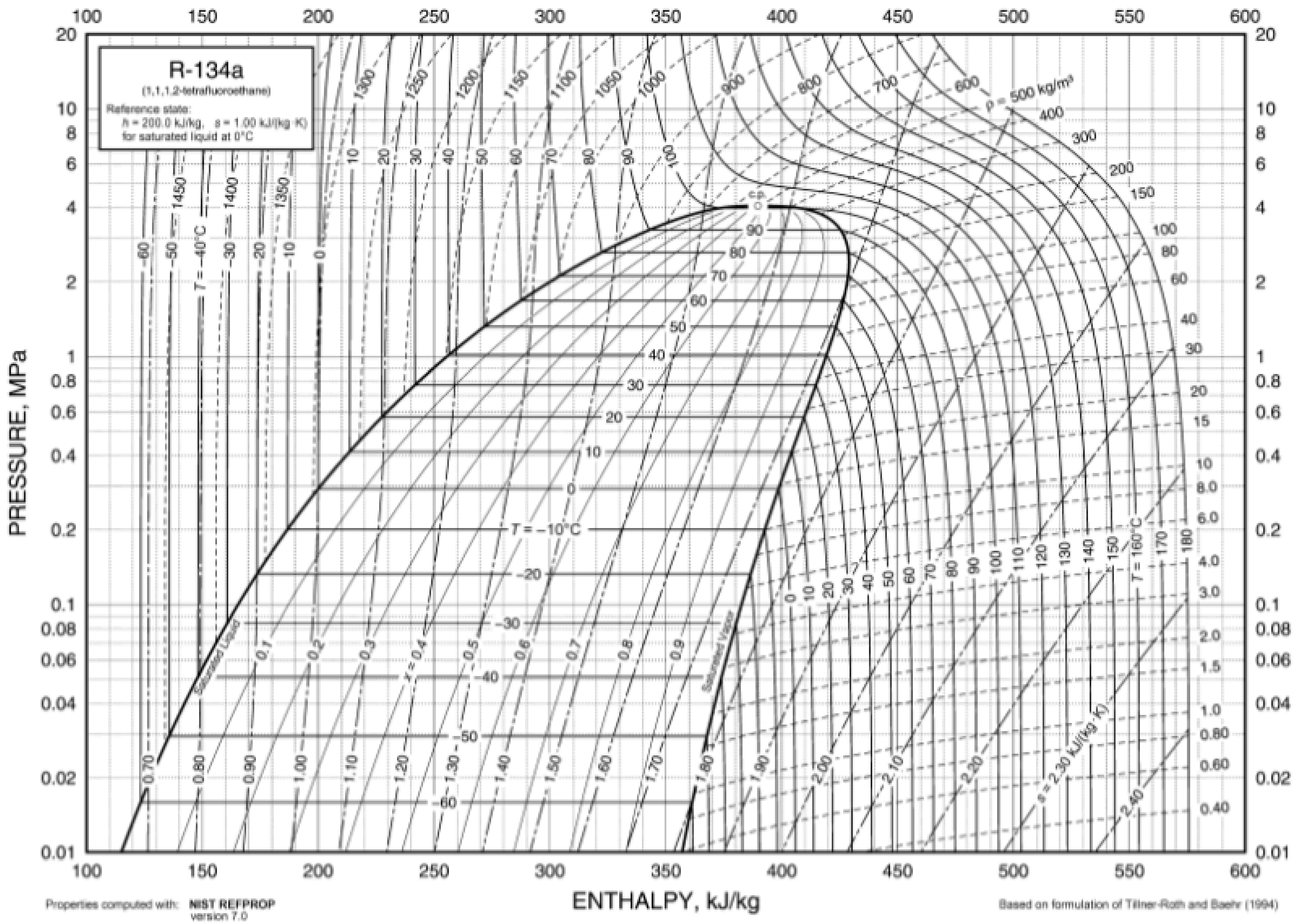


(c) www.ashrae.org 2017 ASHRAE IP Fundamentals Handbook Figure 30.8



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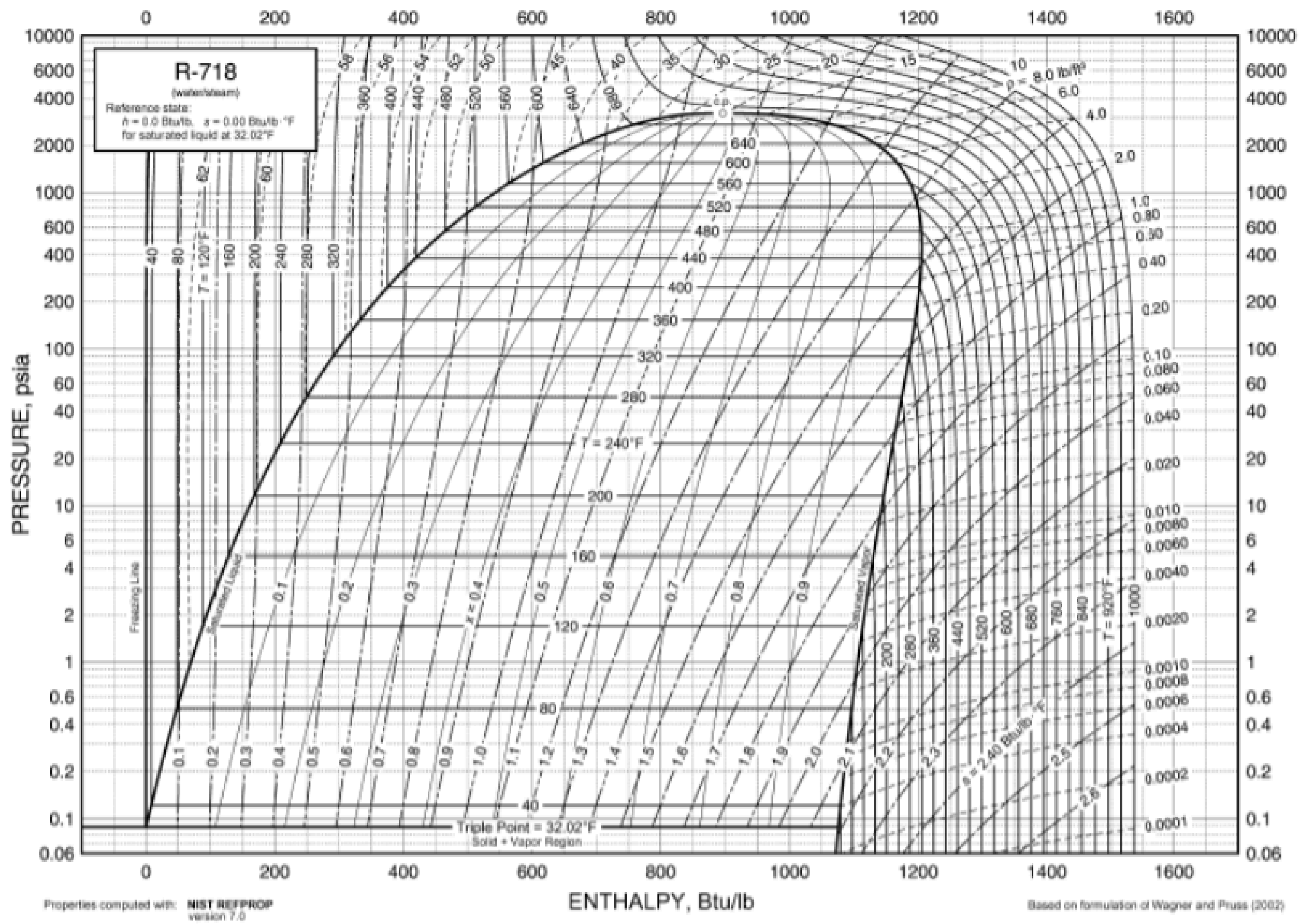
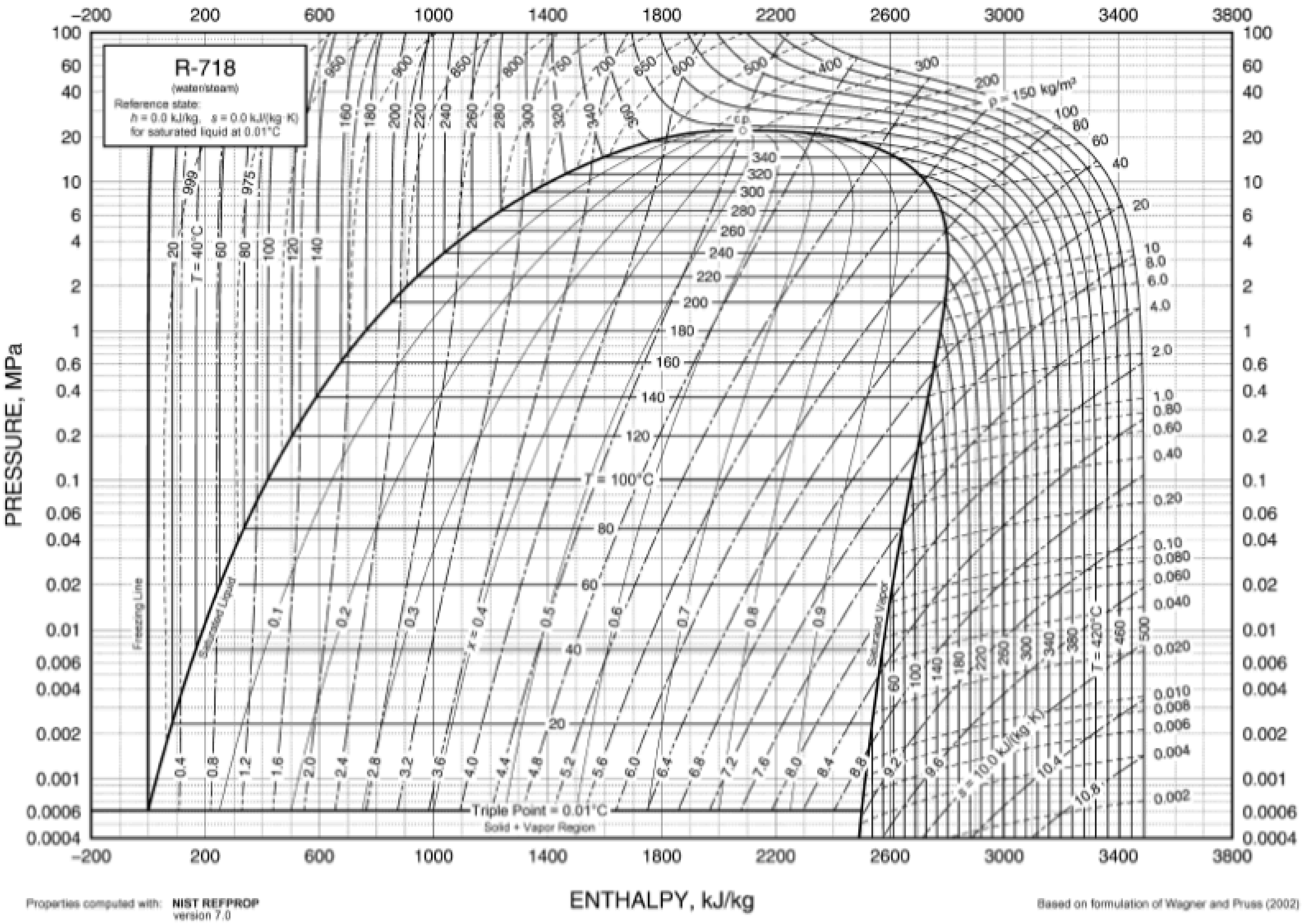


(c) www.ashrae.org 2017 ASHRAE IP Fundamentals Handbook Figure 30.20



(c) www.ashrae.org 2017 ASHRAE SI Fundamentals Handbook Figure 30.20