AC 2010-47: ENGINEERING THERMODYNAMICS - A GRAPHICAL APPROACH

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Engineering Thermodynamics – a Graphical Approach

Abstract

This paper presents the first open-source web-based thermodynamic learning resource. The completely self-contained project is found at http://www.ent.ohiou.edu/~thermo. This web-book was designed for a two-course sequence in thermodynamics for Mechanical Engineering majors, and contains several unique pedagogical features that will be discussed in the paper. When coupled with the open-source nature of this effort, and the additional advantages of convenient classroom presentation, no textbook required, the ability for instant updating, and worldwide relevant links and interaction, we believe that this effort represents a significant improvement in thermal science education.

In this web-book thermodynamics is introduced starting with the First Law and its application in analyzing complete ideal Stirling and air-standard engine cycles, steam power plants, and refrigeration systems. A unique feature of the web-book is the extensive use of pressure-enthalpy (*P-h*) diagrams that enable intuitive visualization of even the most complex steam power plants to a high degree of accuracy. This is contrary to all current thermodynamic textbooks in which temperature-entropy (*T-s*) diagrams are used to represent steam power plants. This standard textbook approach is non-intuitive in that there is no indication of the turbine power output, and incorrect in that the ideal feedwater pump process is always represented by a line when in fact it should be closer to a single point.

Another significant departure from traditional thermodynamic texts is the use of the ideal Stirling cycle machine to represent the ideal reversible machine. The ideal Stirling cycle machine has a thermal efficiency equivalent to that of the Carnot cycle machine, and is much simpler to analyze. The ideal Stirling cycle and its thermal efficiency are analyzed immediately after introducing the First Law.

In addition to the analysis of the traditional fluorocarbon (R134a) refrigeration cycle, the transcritical carbon dioxide (R744) refrigeration cycle is also developed. Because of global warming concerns, the currently used refrigerant R134a is due to be banned from usage in European automobile air-conditioning systems within a few years. The alternative being developed is a return to CO_2 as a refrigerant.

Background and Structure of the web-based learning resource

Having taught Engineering Thermodynamics continuously since 1990, and previously spending 7 years in the thermal sciences industry, I have seriously evaluated nearly every thermodynamic textbook available. In spite of periodically coming out with expensive new editions, almost all such texts have a number of pedagogical disadvantages and fail to significantly address the major advances in the field in response to the energy and global warming crises. Such shortcomings must be addressed to improve student readiness to face critical future energy engineering challenges.

In 1999 I started to develop a web-based supplement to enhance the textbook material I used in teaching Thermodynamics. At some stage in this development I realized that the textbook was almost unnecessary. During winter of 2009 I was awarded Professional Leave in order to develop a complete open-source web-based learning resource independent of any textbook. This was successfully completed and can be found at http://www.ent.ohiou.edu/~thermo.

The basic structure of this web-based resource is similar to that of a textbook. It includes eleven chapters and is divided into two parts. The first part is designed as an introduction to engineering thermodynamics for students of all engineering majors, and is structured as follows:

Part 1 – An Introduction to the First and Second Laws of Thermodynamics

- Chapter 1: Introductory Concepts, Units and Definitions
- Chapter 2: Properties of Pure Substances
- Chapter 3: The First Law of Thermodynamics for Closed Systems
    - (Includes Ideal Stirling engines, and Air-Standard Diesel and Otto cycle engines)
- Chapter 4: The First Law of Thermodynamics for Control Volumes
    - (Includes analysis of steam power plants and refrigeration systems)
- Chapter 5: The Second Law of Thermodynamics
- Chapter 6: Entropy – A New Property

Notice that the main approach of this engineering thermodynamics web resource is to relate all aspects of the course to practical real world applications as soon as the analysis techniques become available, thus already in the third week after introducing the First Law we analyze complete heat engine cycles including the ideal Stirling engine and air-standard Diesel and Otto cycle engines. The Stirling cycle machine is becoming more significant for both distributed power and refrigeration applications[1], however it is only briefly covered in the various textbooks.

Furthermore, the web resource is based on the assumption that the student can obtain an immediate intuitive understanding and basic evaluation of thermodynamic systems through visual graphical means, in which the various processes are sketched on property graphs. From the Fundamentals of Engineering Reference Handbook[2] we see that this has been the current practice in industry in relation to the use of the pressure-enthalpy diagram for refrigeration systems, and psychrometric charts for air-conditioning systems, however it is sadly lacking in steam power plants. In this web learning resource graphical techniques are emphasized and developed throughout.

Part 2 of the web resource is designed specifically for mechanical engineering majors and is structured as follows:

Part 2 – Applied Engineering Thermodynamics

- Chapter 7: Exergy – Maximum Available Work Potential
- Chapter 8: Steam Power Cycles
    - (Including regenerative cycles – open and closed feedwater heaters)
- Chapter 9: Carbon Dioxide (R744) - The New Refrigerant
- Chapter 10: Air – Water Vapor Mixtures
- Chapter 11: Combustion

Advantages of a web learning resource

There are a number of advantages to an open-source web-learning resource:

1. Instant updating options – this applies to both error corrections (students delight in finding and pointing out errors), as well as keeping up with the evolving energy field. I continually receive email comments and constructive criticism from throughout the world. One does not have to wait for a new edition to come out.
2. Worldwide relevant links and interactions. Thus, for example, instead of simply discussing the importance of a consistent system of units, we have a web link to the official NASA website concerning the Mars Climate Orbiter disaster of 1999, due to one team using the English system of units while the other team used the metric system.
3. Convenient classroom presentation, in particular with respect to the graphical techniques. In contrast to a PowerPoint presentation, students can review the material at any time on the web prior or subsequent to the formal presentation.

In the following we present the various unique pedagogical features of this web learning resource.

Early analysis of complete cycles and systems

Most standard introductory sections of Thermodynamic textbooks cover the First Law in terms of processes and components, and completely ignore the more interesting synthesis of these into complete cycles and systems. All the tools are available to evaluate heat engines, steam power plants, and refrigeration systems immediately after introducing the First Law, however this is considered to be advanced material to be covered in later chapters.

In this web resource the ideal Stirling cycle engine is first analyzed and found to have a thermal efficiency equal to that of a reversible heat engine long before any consideration of the Second Law. Furthermore, following Potter and Somerton[3], the adiabatic process relations are developed from the energy equation rather than from the entropy relations, thus enabling a meaningful early analysis of air-standard Diesel and Otto cycle engines.

Graphical approach to analysis

After introducing the First Law for control volumes in Chapter 4, steam power plants and refrigeration systems are analyzed. The pressure-enthalpy (P-h) diagram has traditionally been used to represent refrigeration systems, and in the Fundamentals of Engineering Reference Handbook[2] it is used exclusively in order to answer questions on refrigeration, however this is not the case for steam power plants. In all textbooks that we are aware of the temperature-entropy (T-s) diagram is used to represent steam power plants. This is non-intuitive in that it is very difficult to determine the power output or the efficiency of the power plant, and it is extremely difficult to represent any of the common complexities found in steam power plants, including throttling control valves, and open- and closed-feedwater heaters. Furthermore it is incorrect, since the ideal feedwater pump is always represented on the T-s diagram as a vertical line, when in fact for an incompressible liquid it should be closer to a single point.

The only use that we can think of for the *T-s* diagram is the qualitative comparison of an ideal Rankine steam power cycle to that of a Carnot cycle. This is always done in terms of a distorted sketch and never to scale, since it is extremely difficult to correctly display processes in the compressed liquid region. Furthermore, since the *T-s* diagram can only be discussed after introducing the concept of entropy, steam power plants are normally considered to be an advanced subject.

In this web resource the *P-h* diagram has been developed to represent steam power plants similarly to its use in refrigeration systems, and we find that all of the above problems are easily resolved. For example consider the super-critical steam power plant example shown in Figure 1.

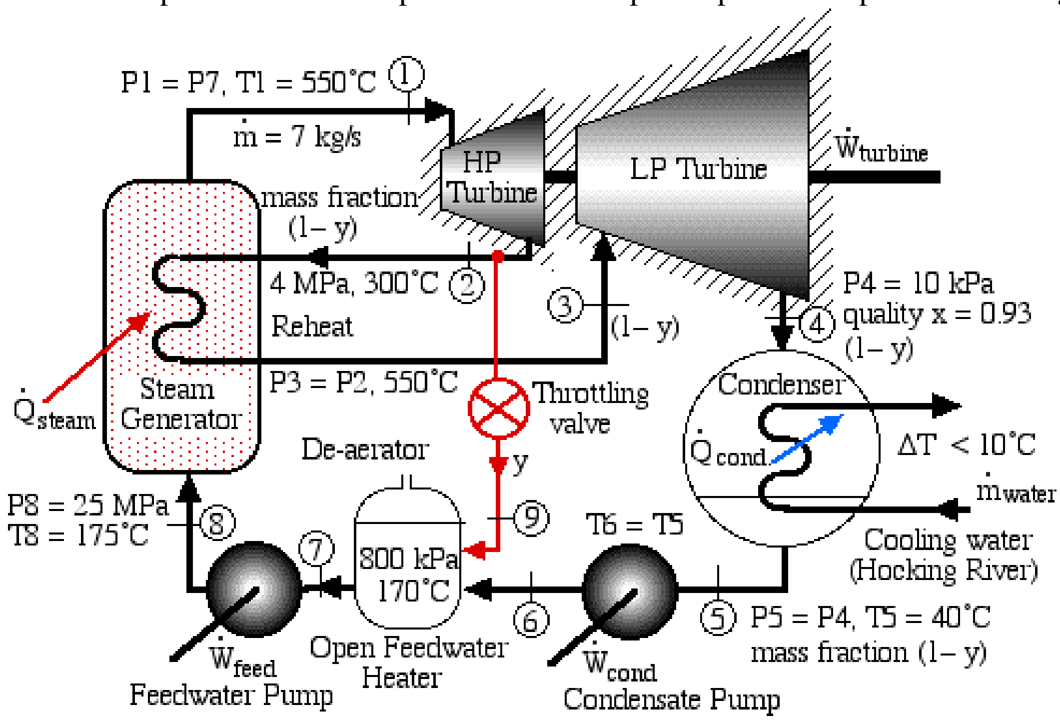

Figure 1 - Super-critical Steam Power Plant Example

This example is taken from Chapter 4 and is normally developed during the fourth week of the basic thermodynamics course. In spite of its complexity, the entire steam power plant can be easily represented on the *P-h* diagram by straight lines, as shown below in Figure 2. The student can determine the performance of the plant, including power output, the mass fraction (y) of the steam bled from the HP turbine outlet, and the thermal efficiency of the power plant, directly from the *P-h* diagram to a high degree of accuracy by simply comparing the various relevant enthalpy differences.

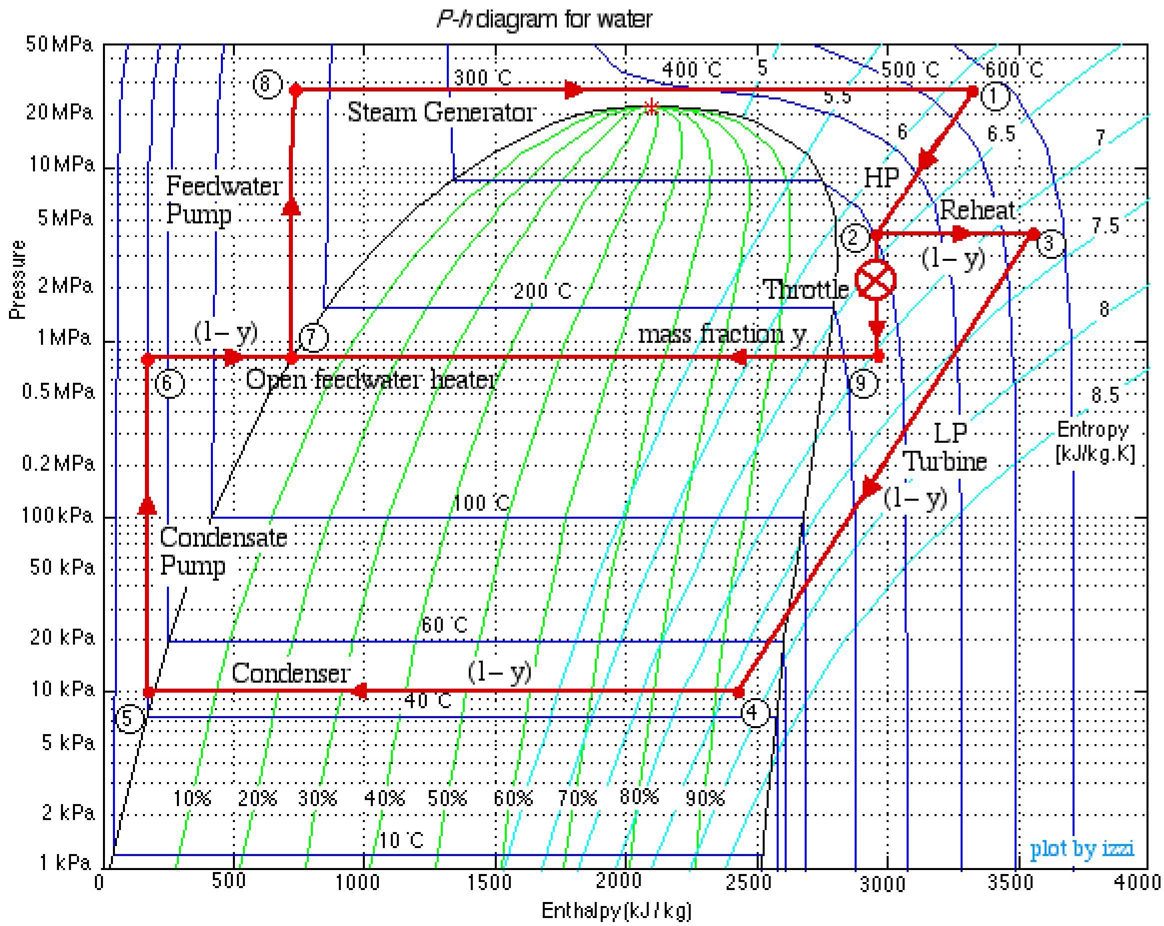

Figure 2 – Pressure-enthalpy (*P-h*) diagram for water-steam

The *P-h* diagram can be used to evaluate highly complex steam power plant systems, such as the 2.6GW Gavin steam power plant located in Ohio. Each of the two units include six turbines, one open- and seven closed-feedwater heaters, and forms the major case study of the web learning resource, thus validating this graphical approach to analysis[4].

The only important parameter that is not easily evaluated from the pressure-enthalpy diagram is the steam turbine adiabatic efficiency. Following the development of the Second Law we introduce the usage of the enthalpy-entropy (*h-s*) or Mollier[5] diagram as a companion diagram specifically for evaluating the turbine adiabatic efficiency. The Mollier diagram was devised in 1904, and has been used internationally as a graphical aid in steam turbine evaluation.

The two turbines shown in Figure 1 above are plotted on the *h-s* diagram as shown in Figure 3. Notice from the *h-s* diagram plot that one can evaluate the turbine adiabatic efficiency by simply comparing the relevant enthalpy differences of the actual process to those of the isentropic process.

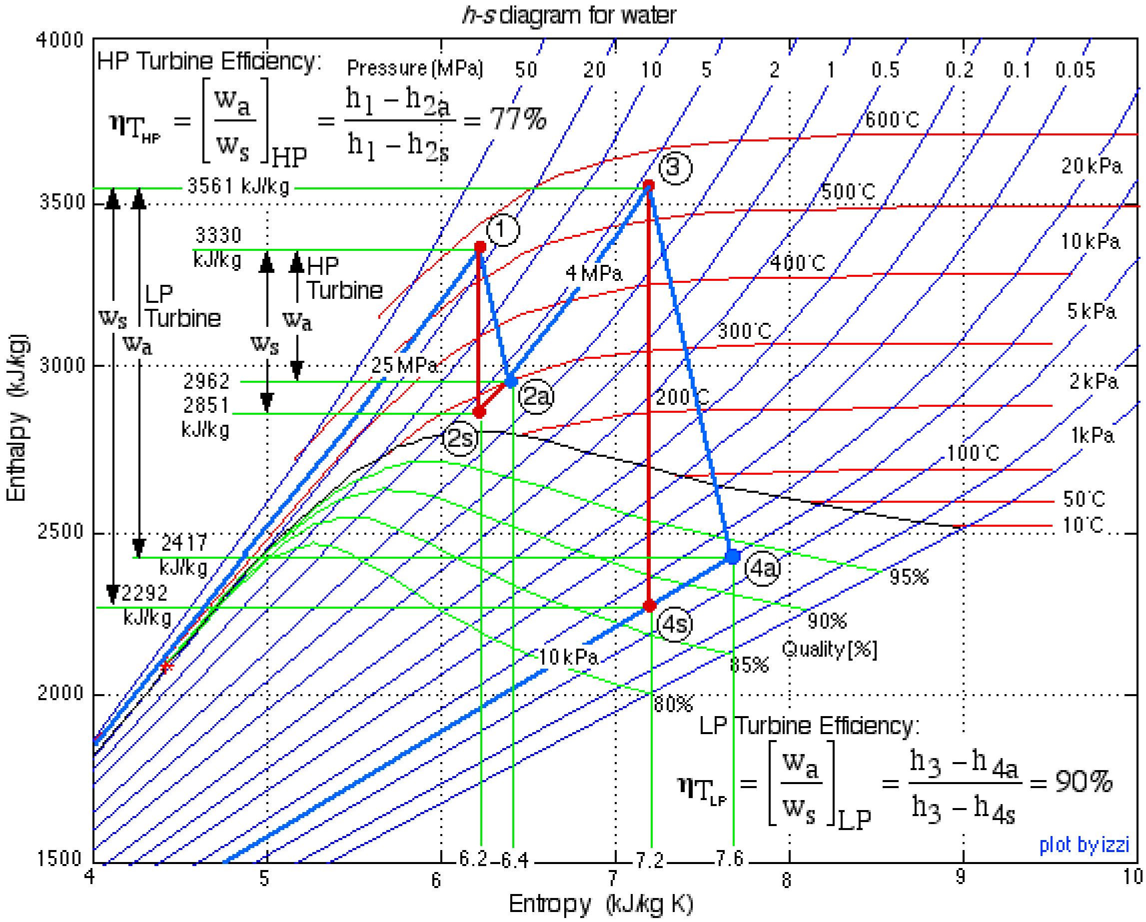

Figure 3 – Enthalpy-entropy (*h-s*) Mollier diagram for water-steam

Stirling cycle machines and the Second Law

In all textbooks reviewed, after developing the Carnot relations from the Second Law, the "Carnot" cycle engine is introduced as the only example of a reversible heat engine, and is represented by the sequence of isothermal and adiabatic processes shown in Figure 4.

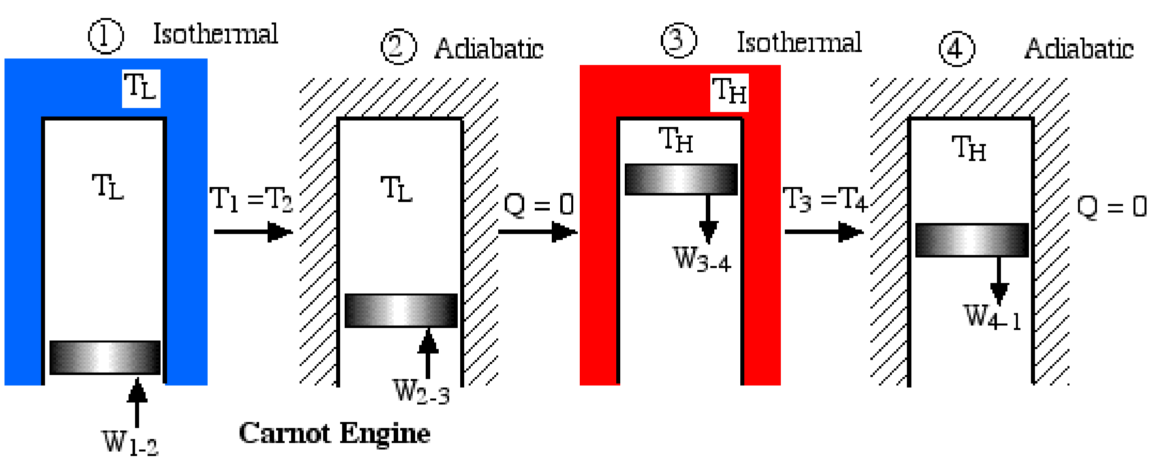

Figure 4 - Carnot cycle heat engine

This is an impractical system to implement, requiring that the surroundings be exchanged between isothermal and adiabatic surroundings after each process. It is also cumbersome to analyze due to the end points of each process being functions of the temperature extremes as well as the compression ratio, and are not easily defined. We prefer to use the ideal Stirling cycle engine as the prime example of a reversible heat engine. The ideal Stirling cycle engine was previously evaluated in Chapter 3 and is at this stage familiar to the students. It is the only practical machine that is reversible in its ideal form, and thus can be operated either as a heat engine or a heat pump. The ideal Stirling cycle heat engine can be represented by the sequence of processes shown in Figure 5.

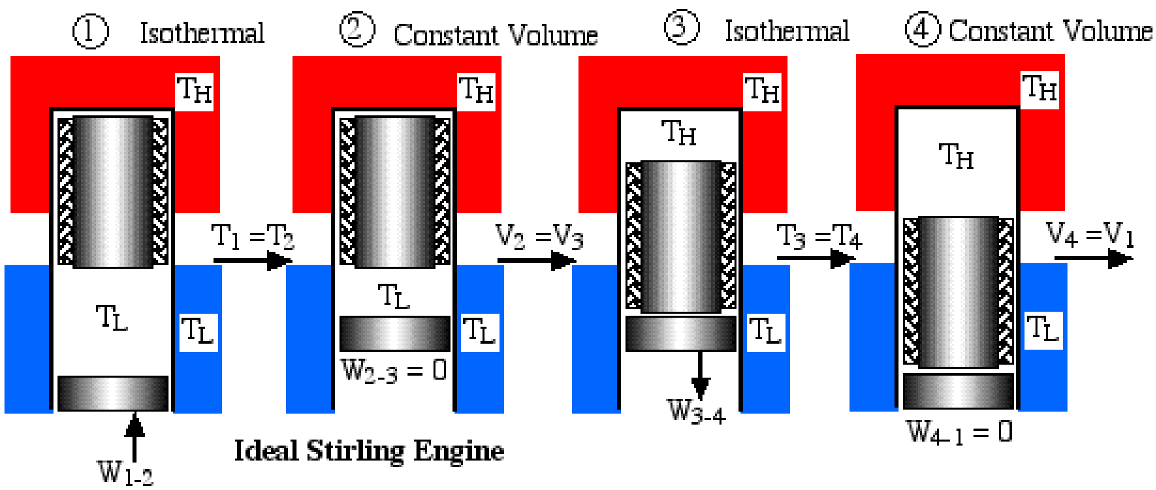

Figure 5 - Ideal Stirling cycle heat engine

Notice that instead of replacing the surrounding environment as is done in the Carnot engine, we simply shuttle the working gas between the hot and cold spaces using a displacer piston. Notice that process 4-1 is a constant volume displacement process in which a significant amount of heat is transferred to the regenerator matrix shown surrounding the displacer piston, which is subsequently recovered during the constant volume displacement process 2-3. Thus for an ideal regenerator matrix the two constant volume processes are externally adiabatic, which is a basic requirement for a reversible heat engine.

Furthermore, on examining the pressure-volume (P-v) diagram, the Stirling cycle engine will provide the maximum net work per cycle under the bounds of volume, pressure, and temperature, as can be seen on the P-v diagram in Figure 6, comparing a Stirling cycle engine to a Carnot engine.

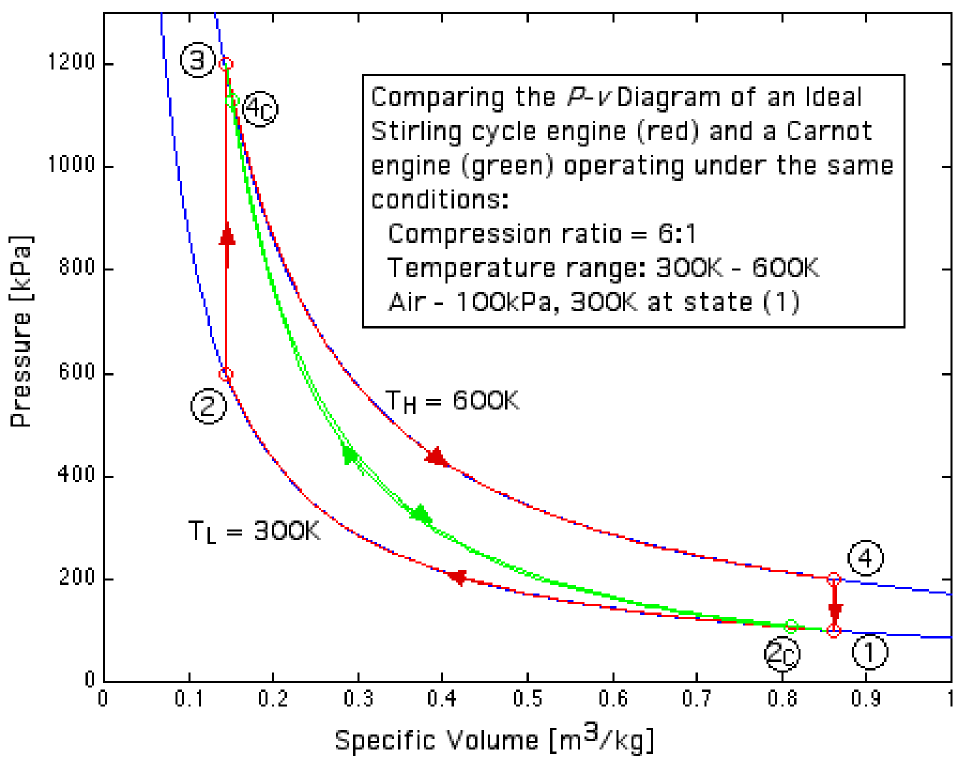

Figure 6 – Pressure-volume (*P*-*v*) diagram of Stirling and Carnot engines

Carbon dioxide refrigeration

In the early days of refrigeration the two refrigerants in common use were ammonia and carbon dioxide. Both were problematic - ammonia is toxic and carbon dioxide requires extremely high pressures (from around 30 to 200 atmospheres) to operate in a refrigeration cycle, and since it operates on a transcritical cycle the compressor outlet temperature is extremely high (around 160°C). When non-toxic Freon 12 (dichloro-diflouro-methane) was developed in 1930 it became the refrigerant of choice. Unfortunately, when this refrigerant does ultimately leak and make its way up to the ozone layer the ultraviolet radiation breaks up the molecule releasing the highly active chlorine radicals, which help to deplete the ozone layer. Freon 12 has since been banned from usage on a global scale, and has been essentially replaced by chlorine free R134a (tetraflouro-ethane).

Recently, however, the international scientific consensus is that global climate change is caused by human energy related activity, and various man made substances are defined on the basis of a Global Warming Potential (GWP) with reference to carbon dioxide (GWP = 1). R134a has been found to have a GWP of 1300 and in Europe, within a few years, automobile air conditioning systems will be barred from using R134a as a refrigerant[6,7].

The new hot topic is a return to carbon dioxide (R744) as a refrigerant[7,8]. The previous two major problems of high pressure and high compressor outlet temperature are found in fact to be advantageous. The very high cycle pressure results in a high fluid density throughout the cycle, allowing miniaturization of the systems for the same heat pumping power requirements. Furthermore the high outlet temperature will enable instant defrosting of automobile windshields (we don't have to wait until the car engine warms up) and can be used for combined space heating and hot water heating in home usage at a significant economy over the regular gas or electric hot water heater[8]. Consider the following system diagram shown in Figure 7.

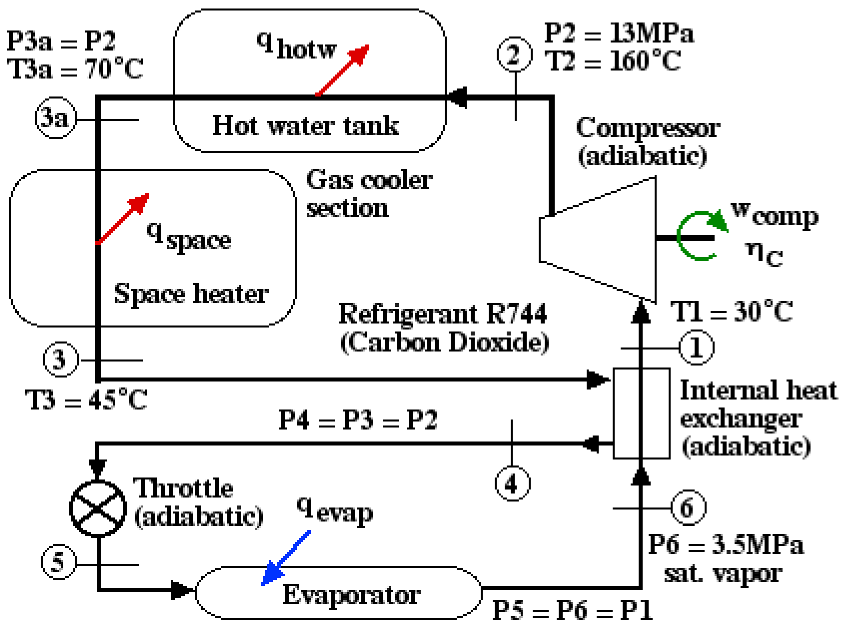

Figure 7 – Carbon dioxide air conditioner / hot water heater system

We notice the use of an internal heat exchanger that is not normally found in a refrigeration system, and from the system diagram it is difficult to justify this added complexity. Nevertheless the entire system is easily represented on the pressure-enthalpy (*P-h*) diagram by straight lines as shown in Figure 8, giving us an immediate intuitive understanding of the importance of the internal heat exchanger. From Figure 8 we see that the transcritical nature of the gas cooling process 2-3 severely restricts the amount of heat absorbed in the evaporation process. By subcooling the gas from state 3 to state 4 we find that we have significantly increased the amount of heat absorbed in the evaporator (process 5-6). It is not even necessary to do a heat exchanger analysis in order to determine the enthalpy at state 4, since we notice that the enthalpy difference of process 6-1 is equal to that of process 3-4.

In 2005, we were informed that it has become common practice in the conventional refrigeration industry to use an internal heat exchanger to subcool the R134a refrigerant at the outlet of the condenser in order to increase the refrigeration capacity as described above, as well as to ensure superheating of the refrigerant prior to compression (Ungar[10]). One approach to achieving this is to simply wrap the capillary tube (throttle) around the tube connecting the evaporator to the inlet of the compressor, allowing increased refrigeration capacity without modifying any of the system components. On researching this process we found that it was described in only one of the examined thermodynamics texts (Wood, 1969[11]).

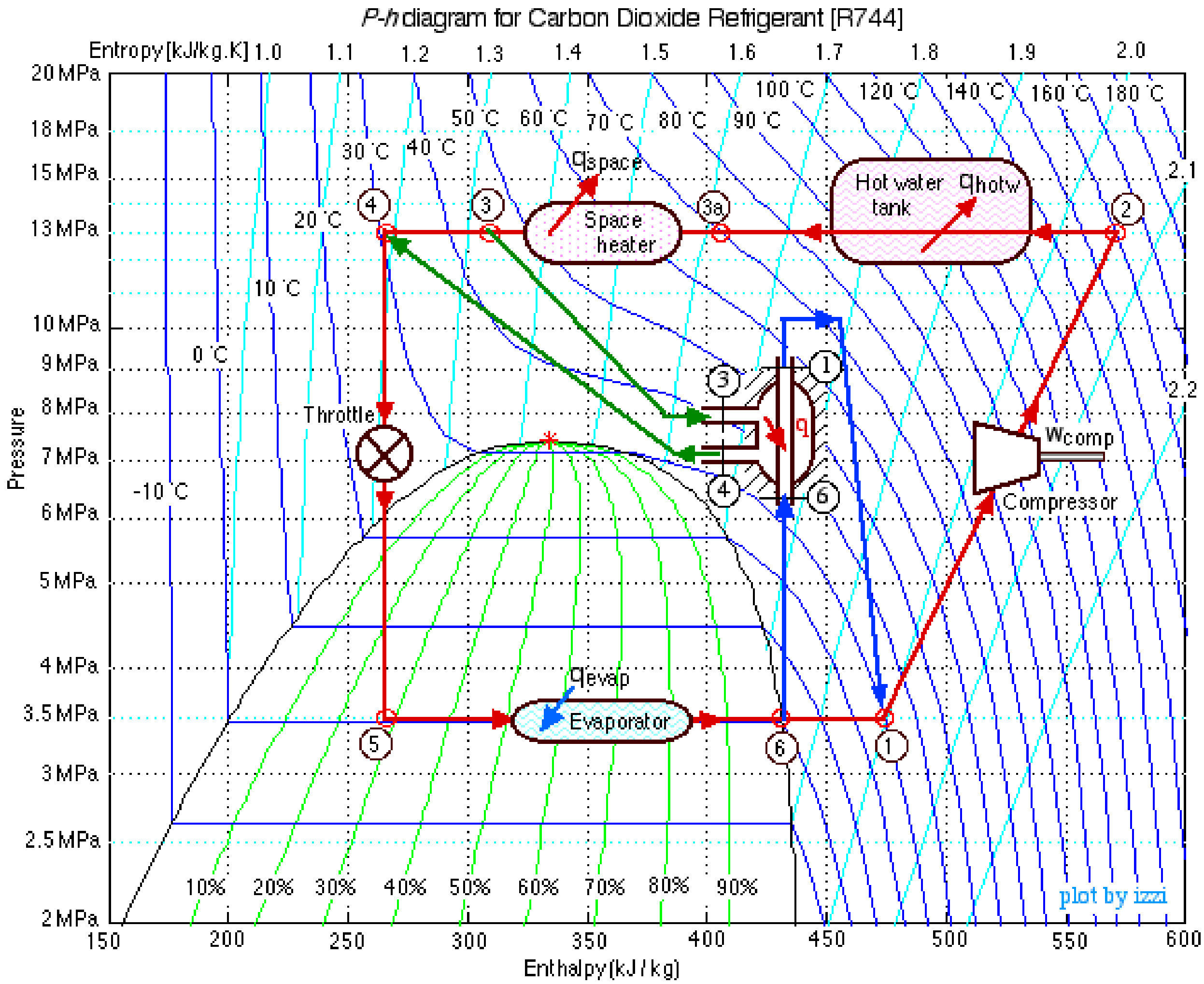

Figure 8 – Pressure-enthalpy (*P-h*) diagram of carbon dioxide

Psychrometrics

It is well known that humans feel comfortable in an environment that is restricted to a specific range of temperatures (22˚C – 27˚C) and relative humidity (40% - 60%). However relative humidity cannot be directly measured, and is a complex function of the air temperature, pressure, amount of water vapor in the air, and can only be indirectly evaluated through a wet- and dry-bulb thermometer. This has lead to the psychrometric chart being the traditional graphical means of designing and evaluating systems for air conditioning as well as cooling tower applications, and in the Fundamentals of Engineering Reference Handbook[2] it is used exclusively in order to solve problems on air conditioning. The psychrometric chart is however extremely busy, involving six interconnected variables, and is thus challenging for students to comprehend.

Following an approach suggested by El-Shaarawi[12], simplified approximations of the various psychrometric relations have been developed in Chapter 10 of the web resource, thus allowing the students to plot their own simplified version of the psychrometric chart using a MATLAB program. This in turn promotes a deeper appreciation and understanding of the psychrometric chart and its application. An example of the chart and its application is shown below, in which outside air at 35˚C and 60% relative humidity is to be conditioned so as to bring the air to within the "comfort zone". The entire problem is solved graphically on the psychrometric chart, leading to the solution as shown in Figure 9.

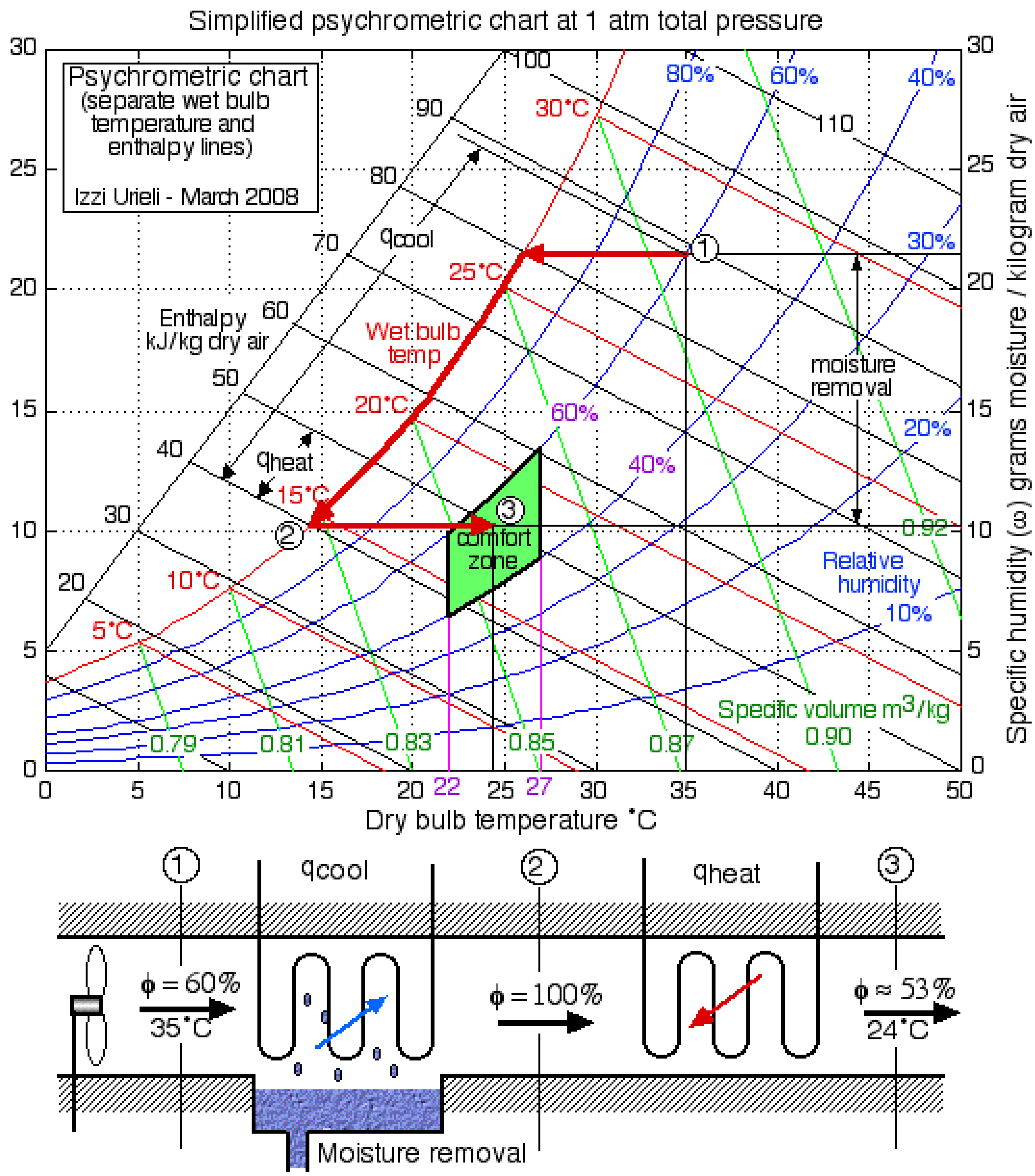

Figure 9 – Typical air conditioning application shown on a psychrometric chart

Student/faculty comments and objective assessment

At the time of writing this paper the web learning resource has been used as the exclusive text for two Introduction classes and two Applied Thermodynamics classes by two faculty instructors, involving around 130 students, over a period of less than a year. Throughout this period there has been almost daily email interaction with students, faculty, and interested observers from all over the world. (As of February 2010, if one Googles "Thermodynamics graphical" then this web resource appears within the first few hits out of more than a million). Critical review by faculty instructor Bayless[13] resulted in a complete rewrite of the final chapter on Combustion.

From Student Surveys done at the end of each course the response has been mainly positive, with Strong Agreement and Agreement being the only two responses that the course was appropriate for the required learning outcomes. Some of the representative written comments follows:
"I believe that the graphical method learned in class was very beneficial to my understanding of the problem. It really helped because you could actually see how the system functioned."
"I really liked the web resource. It threw out all the extra nonsense that nobody looks at in textbooks. I think more classes should look into doing the same thing."
We realize that these are subjective observations, however both courses undergo regular objective assessment of the specified student learning outcomes. The Introduction to Thermodynamics course is continually assessed as a Program Indicator for ME majors, and includes a Mastery learning objective for the ABET evaluation process defined as follows:
"An ability to solve common engineering problems, including problems involving

> The application of the first law of thermodynamics to the analysis of energy components and systems including at least one of the following [Mastery, PI]
>
> 1. Ideal Stirling and air standard power cycles
> 2. Steam power plant components and systems
> 3. Refrigeration and heat pump components and systems"

After the web resource was introduced, the Spring 09 assessment summary for this objective included the following: "All of the items were covered in class and in the web learning resource that was specifically designed around this outcome. Because of the significant repeated quiz and exam content and activity relating to First Law analysis of heat pump components and systems, it is not possible to pass this course without satisfying this outcome."

Conclusions

There are a number of pedagogical issues which make this web learning resource a significant departure from the standard approach. All textbooks that we have reviewed treat the temperature –entropy (T-s) diagram as the most important graphical description of complete systems, which is probably the main reason why systems are not normally covered until after the Second Law has been developed. Our web learning resource uses the much more intuitive pressure-volume (P-v) or pressure-enthalpy (P-h) diagrams which enable early meaningful evaluation of complete practical real world systems. No textbook that we are aware of uses the P-h diagram for steam power plants, and many of them only briefly describe their use in refrigeration systems. After development of the Second law, we introduce the companion enthalpy-entropy (h-s) diagrams, and find this approach to be sufficient for a complete coverage of all the required material.

In some textbooks there is only a superficial coverage of Stirling cycle engines, however there is no coverage of the Stirling cycle refrigerator. Both are covered early in the web resource.
No textbook that we are aware of mentions the extremely high global warming potential of the current refrigerant R134a or the renewed interest in carbon dioxide refrigeration. A complete chapter is devoted to carbon dioxide refrigeration in the web resource

It is an ongoing interactive project, and as feedback is received from students, and emails are received internationally, the web resource is continually being updated and revised. We continually enrich the web resource with real world problems as we become aware of them, and include relevant web links wherever appropriate.

Acknowledgements

A thermodynamics resource cannot be realized without tables of properties of the various fluids, for the plotting of the property diagrams and for the numerical solution of the problems. Particularly for an open-source web resource we needed open-source property data available on the web. We are deeply grateful that this service has been provided by the NIST in their Chemistry WebBook[14], since without this resource we would not have been able to complete this project. We obtained additional data needed to complete the tables from a web resource by Bhattacharjee[15] called TEST (The Expert System for Thermodynamics).

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