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Aren't Units Part of the Problem?

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abstract

Employment data shows that the bulk of engineering graduates who are successful at finding engineering-related employment are hired by the manufacturing, construction, and government sectors. Industry feedback indicates a perceived weakness in the critical thinking and problem solving skills of our engineering graduates. This paper advocates developing more rigorous unit analysis skills and use of conventional units that will be seen by graduates entering the workforce as a part of the academic solution to the reported problem. For engineers working in the United States, that means practicing with the United States Customary System (USCS) of units and with industry-specific units. Familiarization with the analytical framework of the potential employer’s engineering applications can facilitate job interview performance and assimilation. Proficiency in calculations conducted in USCS reduces the job-specific training that must be accomplished by many American employers to get their new engineers ready to work. This paper reviews the history of American units and provides examples of dimensional analysis.

introduction

The purpose of this paper is to address the cognitive connection between proficiency in unit analysis and problem solving skills. The double entendre of the title is intentional. Continuing feedback from American industry, as regularly reported in ASEE literature and at ASEE conferences, indicates a perceived weakness in the critical thinking and problem solving skills of our engineering graduates. Most of our graduates enter industry and must not only assimilate to the demands of the new work environment, but also must develop proficiency in the unit systems used by their new employers. In spite of multiple federal and state laws mandating the shift to Systeme International (SI), large portions of American industry and commerce have resisted shifting to metric units. Personnel re-training costs, fear of expensive mishaps during transitions, the large preponderance of legacy systems and equipment utilizing customary units on their gages and other instruments, and the intransigence of the American people all contribute to maintaining traditional unit systems.

On the other hand, our education system from the secondary level up through the university level has adopted SI units in the science and engineering curricula. And SI is the specified language of our academics as specified by the journals which publish their work. More recently written engineering textbooks continue this pattern and some have dropped USCS altogether. This reality has created a unit system challenge for our graduates, one that essentially shifts mastering the traditional units of their new employers to the workplace – they need proficiency in traditional units, but have mainly been exercised in SI. In addition, unit conversion skillsets are not exercised to the same degree in the SI system. Add to that the growing use of computer-based homework which provides quick feedback on the numerical answer, but may not reinforce unit analysis skills.

In light of industry feedback, are we engineering educators doing a disservice to our students by neglecting or underexposing them to how to perform engineering analyses in the units that are customary to their prospective employers? Would those hiring our graduates be better served and hold a higher opinion of our product if we exercised our students more in conventional unit systems? This paper explores these questions and provides examples of a systematic methodology that is proven to develop student competence in practical problem solving.

background

The background of a discussion about engineering units is rooted in the topic of weights and measures. The history of weights and measures is the history of human trade. Knowing what one was buying or trading for and how much of it was expected in the transaction were significant issues. Among ancient texts that address the topic, the Laws of Moses from the second millennium B.C. includes, "You must have accurate and honest weights and measures, so that you may live long in the land the Lord your God is giving you. For the Lord your God detests anyone who does these things, anyone who deals dishonestly."[1] The issue of weights and measures has existed for a long time.

At the time of American Independence, the weights and measures in common use were practically all of English origin, but not necessarily uniform.[2] The basic units existed in the quantities that are familiar today. Although there were (and continue to be) other weight systems based upon a unit called a pound, the avoirdupois pound was based upon 7,000 grains – the weight of 7000 dry barley grains.[3] The length units of foot and inch are based upon the yard, which had last been standardized by Elizabeth I in 1588.[4]

The Articles of Confederation (1781) and the Constitution (1787) gave Congress the authority "To coin Money, regulate the Value thereof, and of foreign Coin, and fix the Standard of Weights and Measures." Standardization of weights and measures and the availability of physical standards as references for measurements, however, was an unresolved issue for decades into our young country's existence. This situation caused significant confusion in international and interstate trade and inconsistent collection of import duties. And recall that unfair taxation was one of the issues that lead to the War for American Independence. Fixing this was a matter of principle. However, even with decades of advocacy and effort it was not until the 1830s that a uniform set of standards was achieved by the Department of the Treasury for use in the United States. The official policy of the United States was to synchronize our standards with those of Great Britain. The standards established at this time included the yard of 36 inches, the avoirdupois pound of 7,000 grains, the gallon of 231 cubic inches, and the bushel of 2,150.42 cubic inches.[5]

What has become the "metric system" originated with recognition of decimal relationships made possible with the Arabic numbering system, as opposed to the Roman numeral system used throughout much of Europe. The concept of a unified and common unit system was gaining ground, but it was the French Revolution that provided the impetus to establish a unit system that was rationally based upon nature and had a decimal relationship between the quantities. There were alternate systems proposed during this development. In the 1790s, the meter was defined as 1/10,000,000 (one ten-millionth) of a quadrant meridian of the earth (essentially the distance from the North Pole to the equator). Then a liter of volume followed as the cube of 1/10 of a meter (a decimeter), which is one thousandth of a cubic meter. A kilogram of mass followed from that as the mass of cold water that occupied a liter (originally measured at 0 ^{o}C and then adjusted in 1799 to be measured at water's peak density occurring at 4 ^{o}C).[6] There was a desire to develop basic units which were within the ability of a person to hold. A meter, liter, and kilogram satisfied this need.

While the Americans were establishing their weights and measures based upon British conventions, the British were reforming theirs. The 1824 Weights and Measures Act of the English Parliament established the Imperial gallon as the volume of 10 pounds of water at 62 ^{o}F (277.421 in^3). This replaced the "ale gallon," which had been standardized by Parliament at 282 cubic inches in 1688, and the "wine gallon," standardized by Parliament in 1707 at 231 cubic inches. Note that the definition of a gallon in the United States is based upon a wine gallon. The fairly standard shipping container of the day was known as a hogshead and was defined as 63 wine gallons, roughly equal to 52.5 ale gallons (in many areas a hogshead of 54 ale gallons was regularly used). The difference in the two volumes is probably rooted in the taxes applied to these two forms of beverage in old England. The U.S. gallon derived from the wine gallon, probably because wine would be exported to the Americas, but ale was not exported to the colonies to the same extent.[7] Even though the metric system was known at the time, the effect of the 1824 Act reinforced the traditional "English" units, rather than adopting the new metric units.

The metric system went through a period of being officially permissible in the U.S. before it was the preferred system. Federal laws enacted in 1866 established the lawfulness of the metric system and directed the production and distribution of standard sets of metric weights and measures to the states for their use. The law did not call for abolishing the customary unit systems.[8] The ensuing period included international negotiations that culminated in an 1875 treaty that established the International Bureau of Weights and Measures in France and a periodic General Conference on Weights and Measures.[9]

In 1893, T.C. Mendenhall, the U.S. Superintendent of Weights and Measures, issued what has become known as the "Mendenhall Order." This document established the international meter and kilogram as the fundamental standards for length and mass in the United States. This essentially ended the ongoing efforts to synchronize the standards of the United States with those of Great Britain. In addition, from this point on, the official conversion tables listed the USCS units referenced to the metric standards instead of vice versa.[10] Then, in 1901, Congress changed the Office of Standard Weights and Measures to the National Bureau of Standards (NBS). NBS subsequently became the National Institute of Standards and Technology (NIST) in 1988.[11] NBS/NIST is the custodian and manager of the weights and standards of the United States.

The metric system continued further definition of various units over the years and added fundamental standards with new technology, such as electricity, magnetism, and light. In 1960, the metric system was renamed, the International System of Units (SI). In 1975, Congress passed the Metric Conversion Act which established the United States Metric Board to coordinate and plan the increased use of the metric system in the U.S. This board was disbanded in 1982. In 1988, Congress included additional metrication language in the Omnibus Foreign Trade and Competitiveness Act. This legislation required federal agencies to use metric system in "procurement, grants, and other business-related activities" by the end of 1992, except for highway and construction projects.[12]

After all of this, the United States has effectively resisted metrication. The scientific community, competitive export industries, and some federal government agencies have adopted the SI system. However, the general American public, domestic industries, construction and maintenance trades, and other sectors of the American economy either do not use SI, or only partially use SI. The de facto condition is a blended system that has been remarkably resistant and yet allowed businesses of the United States to be vibrant and competitive in international trade.

customer focus

As engineering educators, we need to be aware of the requirements of our customers – those who will be buying our product. In this case, that means our engineering graduates. In some locales, that connection is very clear, with the presence of a dominant employer. In others, the connection is less focused. Regardless, engineering educators should consider where their graduates end up obtaining employment and their needs. While it is the reasonable hope of engineering professors that their undergraduate students either go on to graduate studies in engineering or obtain an engineering job, recent statistics tell another story. Here are some factoids about where our graduates go to work:

- 92.5% of the 88,176 Engineering Bachelor's Degrees conferred in 2012 went to permanent residents of the United States.[13]
- In contrast, 43.3% of the 49,372 Engineering Master's Degrees conferred in 2012 went to non-resident aliens.[14]
- 53.9% of Engineering and Engineering Technology graduates are employed in a job in the field of their major one year after graduation.[15]
- 63.7% of Engineering and Engineering Technology graduates are employed in a STEM-related job one year after graduation.[16]
- The Manufacturing and Construction sectors employ 50% to 60% of all engineers.[17]
- Government is a significant employment sector for engineers, especially those involved in building and maintaining public infrastructure and inspecting private construction.[18]

The reasonable conclusion of this is that the majority of our graduates will not go to work where SI is the dominant unit system.

dimensional homogeneity

With 15 years of experience in teaching thermo-fluids courses, and a lot more cumulatively represented in the anecdotes of colleagues, there is a clear sense that students generally prefer to "plug-and-chug" numbers in equations without giving much thought to unit analysis. The advent of the higher end graphing calculators with QWERTY keyboards and a "solve" button has diminished algebraic manipulation skills to solve for the desired variable of complex equations before substituting numerical values. These approaches avoid the necessity of conducting more detailed unit analysis and incorporating appropriate conversion factors. In the SI system, the decimal relationships of many of the terms in an equation often result in the correct number, but perhaps off by some power of ten.

Typically students will need to convert units while solving an equation to be able to add/subtract terms. As an example, consider Bernoulli's equation:

$$z_1 + \frac{p_1}{\gamma} + \frac{\vec{V}_1^2}{2g} = z_2 + \frac{p_2}{\gamma} + \frac{\vec{V}_2^2}{2g}$$

This equation relates pressure (p), velocity ($\vec{V}$), and elevation (z) at two points in a fluid with known specific weight (γ), and can be used to solve for an unknown pressure, velocity, or elevation at one of the points, provided that the correct unit conversions are applied.

<u>Bernoulli Example</u>. Given cold water flowing through an arbitrary shape where z_1 = 100 ft, z_2 = 50 ft, p_1 = 30 lbf/in^2, $\vec{V}_1$ = 25 ft/s, $\vec{V}_2$ = 1ft/s, and γ = 62.4 lbf/ft^3. Since water is essentially incompressible in this range, then the unknown pressure p_2 can be determined by rewriting Bernoulli's equation using algebra as follows:

$$p_2 = p_1 + \gamma(z_1 - z_2) + \gamma\left(\frac{\vec{V}_1^2 - \vec{V}_2^2}{2g}\right)$$

Note that each term has basic dimensions of force per area (length^2) and the rules of algebra demand that the units for each term must be the same before adding and subtracting terms:

$$p_2 = 30\frac{\text{lbf}}{\text{in}^2} + \left(62.4\frac{\text{lbf}}{\text{ft}^3}\right)(100\text{ft-}50\text{ft})\left\{\frac{1\text{ ft}}{12\text{ in}}\right\}^2 + \left(62.4\frac{\text{lbf}}{\text{ft}^3}\right)\left[\frac{\left(25\frac{\text{ft}}{\text{s}}\right)^2 - \left(1\frac{\text{ft}}{\text{s}}\right)^2}{2\times 32.2\frac{\text{ft}}{\text{s}^2}}\right]\left\{\frac{1\text{ ft}}{12\text{ in}}\right\}$$

$$p_2 = 55.87\frac{\text{lbf}}{\text{in}^2}$$

The "railroad track" method is taught to U.S. Navy engineering technicians to provide them with a reliable tool to resolve units, including complex fractions of units. Using the railroad track method to more clearly track the units of this example:

$$p_2 = \begin{array}{c} 30\text{lbf} \\ \hline 1\text{in}^2 \end{array} + \begin{array}{c|c|c} 62.4\text{lbf} & (100-50)\text{ft} & 1\text{ft}^2 \\ \hline 1\text{ft}^3 & 1 & 144\text{in}^2 \end{array} + \begin{array}{c|c|c|c|c} 62.4\text{lbf} & (625\text{-}1)\text{ft}^2 & 1 & 1\text{s}^2 & 1\text{ft}^2 \\ \hline 1\text{ft}^3 & 1\text{s}^2 & 2 & 32.2\text{ft} & 144\text{in}^2 \end{array}$$

$$p_2 = \begin{array}{c} 30\text{ lbf} \\ \hline \text{in}^2 \end{array} + \begin{array}{c|c|c} 21.67\text{ lbf} & \text{ft} & \text{ft}^2 \\ \hline \text{ft}^3 & & \text{in}^2 \end{array} + \begin{array}{c|c|c|c} 4.20\text{ lbf} & \text{ft}^2 & \text{s}^2 & \text{ft}^2 \\ \hline \text{ft}^3 & \text{s}^2 & \text{ft} & \text{in}^2 \end{array}$$

$$p_2 = \frac{30\text{ lbf}}{\text{in}^2} + \frac{21.67\text{ lbf}}{\text{in}^2} + \frac{4.20\text{ lbf}}{\text{In}^2} = 55.87\ \frac{\text{lbf}}{\text{in}^2}$$

As shown in the first line, there is an implied 1 vertically opposite each non-unity value.

Note that the unit fraction of "ft/s^2" (associated with 32.2) is written as the reciprocal in the "railroad tracks" since 32.2 is in the denominator. This follows the rules of complex fractions of multiplying by the inverse of the denominator.

Similarly, the Steady Flow Energy Equation can be applied to a fluid flow power problem in a hydroelectric dam to illustrate additional unit analysis.

Hydroelectric Dam Example. The Conowingo Dam on the Susquehanna River in Maryland was constructed in 1926 and is 4,468 feet long with 100 feet in elevation difference between the upstream and downstream water levels. The dam's crest is 111 feet above the downstream water level. It is one of the nation's largest hydroelectric installations; impounds 105 billion gallons of water in a 14 square mile lake in the Susquehanna River. To reach full output capacity a flow of 85,000 cubic feet per second is required. The tailrace velocity is about 10 mph. The seven original turbine-generators (TGs) are rated at 36 MW each and four TGs added later are rated at 65 MW each. All generators produce power at 13,800 volts, which is then stepped up to 220,000 volts for transmission, primarily to the Philadelphia area. The dam reportedly contributes an average of 1.6 billion kilowatt-hours annually to the electric grid. Calculate the plant overall efficiency. If the plant bids in to the power pool at an average daily rate of $0.05 per kW-hr, what is the gross income per day from operation of this power plant?

$$\dot{m}\left(\frac{gz}{g_c}+\frac{\vec{V}^2}{2g_c}+u+pv\right)_1+\dot{Q}_{12}=\dot{m}\left(\frac{gz}{g_c}+\frac{\vec{V}^2}{2g_c}+u+pv\right)_2+\dot{W}_{12}$$

Establish SP1 on the upstream surface of the water and SP2 on the downstream surface. There is no heat added between the SPs, therefore $\dot{Q}_{12}=0$. The temperature of the water does not change appreciably, so the internal energy (*u*) does not change, nor does the specific volume of the water (*v*). The pressure on both free surfaces is atmospheric pressure. Therefore the change in *u* (Δu) and flow work (Δpv) each cancel. Establish the reference elevation at the downstream surface (SP2). Therefore $z_2 = 0$. There is a downstream velocity. Convert the 10 mph to 14.67 ft/sec. Eliminating terms that either cancel or are negligible results in the following:

$$\dot{m}\left(\frac{gz_1}{g_c}\right)=\dot{m}\left(\frac{\vec{V}_2^{\,2}}{2g_c}\right)+\dot{W}_{12}$$

Solve for the hydraulic power input to the turbines:

$$\dot{W}_{12}=\dot{m}\left[\left(\frac{gz_1}{g_c}\right)-\left(\frac{\vec{V}_2^{\,2}}{2g_c}\right)\right]$$

We'll need the mass flow rate.

$$\dot{m}=\rho\dot{V}=\left(62.4\frac{lbm}{ft^3}\right)\left(85{,}000\frac{ft^3}{s}\right)=5.3E6\frac{lbm}{s}$$

Now let's start working on that reduced form of the SFEE.

$$\dot{W}_{12} = \dot{m}\left[\left(\frac{gz_1}{g_c}\right) - \left(\frac{\vec{V}_2^2}{2g_c}\right)\right] = \left(5.3E6\frac{lbm}{s}\right)\left[\left(\frac{32.2\frac{ft}{s^2}}{32.2\frac{ft-lbm}{lbf-s^2}}\right)100\,ft - \left(\frac{14.67^2\frac{ft^2}{s^2}}{(2)\left(32.2\frac{ft-lbm}{lbf-s^2}\right)}\right)\right]$$

$$\dot{W}_{12} = \dot{m}\left[\left(\frac{gz_1}{g_c}\right) - \left(\frac{\vec{V}_2^2}{2g_c}\right)\right] = \left(5.3E6\frac{lbm}{s}\right)\left[100\frac{ft-lbf}{lbm} - 3.34\frac{ft-lbf}{lbm}\right] = 5.12E8\frac{ft-lbf}{s}$$

$$\dot{W}_{12} = \left(5.12E8\frac{ft-lbf}{s}\right)\left(\frac{hp-s}{550\,ft-lbf}\right)\left(\frac{0.746kW}{hp}\right) = 6.94E5kW$$

This is the power "in" to the turbines from the change in elevation of the water with some unrecovered energy represented in the downstream water velocity. In addition, there are frictional pressure losses in the penstocks, conduits, and flow control gates that are lumped in with the turbine losses.

$$\eta_{oa} = \frac{\dot{W}_{out,oa}}{\dot{W}_{in}} = \frac{7(36,000)+4(65,000)kW}{6.94E5kW} = \frac{512,000kW}{694,000kW} = 73.8\%$$

Another concept that can be brought out in this problem is "brake horsepower." Brake horsepower is measured at a physical rotating shaft at the turbine output coupling. Since each generator is directly coupled to a turbine, the product of the component efficiencies is represented above. So, if the generators are 97% efficient (a typical value), then the turbines are 76% efficient.

Max Power Daily Gross Income = (\$0.05/kW-hr)(1.6E9kW-hr/yr)(1yr/365days) = \$219,178 and the plant workforce is only 55 employees!

<u>Gage Pressures</u>. One of the issues students struggle with is dealing with pressure gages and the variety of pressure units. The American standard pressure unit is pounds per square inch (psi). Very few textbooks exercise gage units for pressure parameters in homework problems and the discussion of what gage pressures mean is usually quite cursory. Oftentimes, however, the stated relationships do not address vacuum conditions and, when vacuum conditions are discussed, the explanatory equations are presented in different forms. Several recent textbooks address this topic with pressure equations stated as, or variations of:

$$p(\text{gage}) = p(\text{absolute}) - p_{atm}(\text{absolute})$$

and

$$p(\text{vacuum}) = p_{atm}(\text{absolute}) - p(\text{absolute})$$

Recognizing that gage pressures are an input to a problem and that the system pressures in absolute terms are needed to use important equations of state (e.g., Ideal Gas Law) and data tables (e.g., Vapor Tables for steam or refrigerants), equations in the form illustrated above appear to students to be two different topics. The more general equation of dealing with pressure gage readings is:

$$p_{system,\,absolute} = p_{atmosphere} \pm p_{gage}$$

This equation is supported by the concepts represented in Fig. 1.

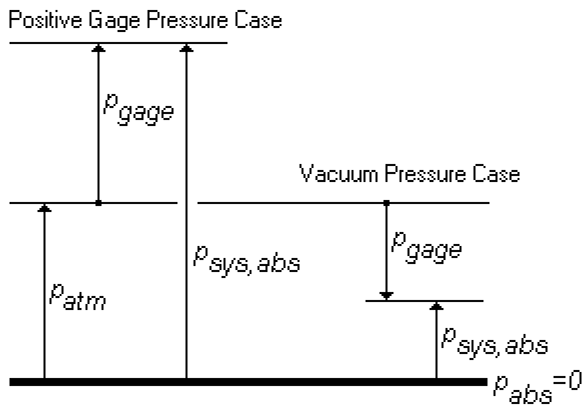


Figure 1

The underlying reason for this situation is that gages are influenced by the local atmosphere in which they are installed. And while a gage measures the pressure via a pressure tap and tube, and may be located at some distance from the location where they are measuring, the local barometric pressure influences the gage reading. Most textbooks do not exercise barometric pressure influences on gage pressure. This effect can be significant when calculating low absolute pressure situations, such as steam cycle parameters in the condenser. And atmospheric pressure is not always at standard sea level conditions.

Using the more general equation associated with Fig.1, students then need to be taught how to recognize which case exists in a given problem. One way to do that is to orient them to the pressure relationship graphic, the industrial application, and the customary units used in that application. Common abbreviations such as psig (gage), psid (difference), psiv (vacuum) should be added to psia (absolute) in their unit vocabulary. Furthermore, manometer units that indicate a vacuum conditions need to be introduced and exercised, such as inches of mercury (in-Hg) and inches of water column (in-w.c.).

The customary unit for condenser pressure in American steam cycle power plants is mercury manometer units (in-Hg). This is a legacy item from the early days of industrialization. Early steam plants fitted with condensers (patented by James Watt in 1769), monitored the system performance with a mercury-filled manometer in order to be able to see the manometer readings within a reasonable height column (a mercury manometer can show in the vertical space of about 30 inches what a water-filled manometer would require almost 34 feet to show). Today, it is still customary to use mercury manometer units for steam condenser pressure, even though bourdon tube gages and electronic pressure transducers long ago replaced manometers in steam plants. Steam plants indicate positive pressures in psig and vacuum pressures in in-Hg.

Another example of an industry retaining manometer units is the HVAC industry. Manometer units in in-w.c. are used for differential pressure measurements in air flow and fuel gas supply pressures (natural gas and LP gas).

Students need to be taught about barometric pressure and be exercised in gage units in order to really comprehend this topic. Our graduates enter a working world with multiple pressure instruments and application-specific units. Let's not pass them on to their future employers ignorant of these concepts.

Basic Steam Plant Example. Boiler pressure is 585 psig and condenser pressure is 27.88 in-Hg; condensate depression is 3.7 ^{o}F; the steam temperature at the turbine inlet is 500 ^{o}F; $\eta_P = 0.8$; $\eta_T = 0.9$. Barometric pressure is one standard atmosphere. Solve for η_{th} of the cycle; steam quality (x) at the discharge of the turbine; and the heat input by the Economizer using the *Steam Tables*.

The State Point Table method of organizing data is very useful and helps students to determine the best way to use the *Steam Tables* for data extraction. Recall that two independent intensive properties are needed to determine the state of the fluid and the related properties. This solution uses the *2000 ASME Steam Tables* for data. So, two independent data entries in a column should allow determination of the rest of the parameters.

STEAM TABLES	**1**	**2s**	**2**	**2'**	**3**	**4s**	**4**
p (psia)	**1.0**	600	600	600	**600**	1.0	1.0
T (^{o}F)	**98.0**	NR (99.8)	NR (100.2)	NR (486.2)	**500**	NR (101.7)	NR (101.7)
h (Btu/lb$_m$)	66.041	67.82	68.28	471.7	1216.5	814.7	854.9
s (Btu/lb$_m$-^{o}R)	NR	NR	NR	NR	1.4597	←1.4597	NR
v (ft^3/lb$_m$)	0.016125	← =	NR	NR	NR	NR	NR
x (%) if WV	NA	NA	NA	0	NA	71.9%	75.8%
State	CL	CL	CL	SL	SHV	WV	WV

"Givens" are **bold**. Be sure to graph the state point locations in the correct regions of the *T*-*s* process graph. CL – Compressed Liquid; SL – Saturated Liquid; SHV – Superheated Vapor; WV – Wet Vapor (aka Saturated Liquid-Vapor Mixture – SLVM).

This problem is different from the "basic" or "ideal" Rankine cycle in that it includes both condensate depression at the exit of the condenser (which is done in reality to protect the pump from cavitation) and slight superheat at the boiler exit/turbine entrance, as well as non-isentropic pump and turbine. The goal is to complete the specific enthalpy (h) row. "NR" identifies cells which are not required to determine the enthalpies for the following state points (directly or indirectly). "NA" means not applicable.

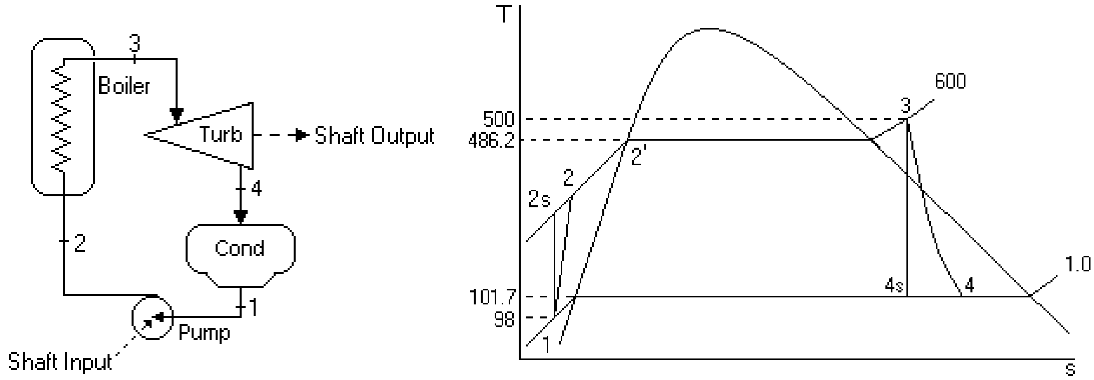
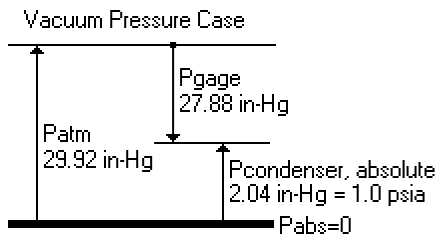


Figure 2

Solution Procedure:

1. Draw the <u>schematic</u>, the <u>*T-s* diagram</u>, (Figure 2) and layout the <u>State Point Table</u> (see above).
    a. The State Point Table is expanded to break out SP2s and SP4s because information is given about η_P and η_T, and they are both < 1.
    b. Determine where to draw SP1, SP3, & SP4, and then draw the process diagram to represent what the states actually are (CL, SL, WV, SV, or SHV). Drawing the *T-s* concept graph is a bit of an iterative process, but should be drawn to represent the proper regions for the state points. It is a good practice to label the pressure lines with their values. Similarly, labeling the temperatures on the graph is a good practice. Note that the *T-s* graph is <u>not to scale</u>. You can see this by noting that SP2 temps are actually lower than T_{sat} for the low pressure condition. The CL lines are exaggerated away from the "vapor dome" for clarity of illustrating the pumping process. There is a loss of scale in doing this, but the pump processes are more easily seen.
    c. SP2' accounts for the Economizer's function. The Economizer is a heat exchanger that pre-heats the feedwater (ideally) to SL conditions.
2. Identify the high and low pressures and fill in the pressure row on the State Point Table.
    a. In this case, the condenser vacuum is given and atmospheric pressure is standard (14.7 psi <u>absolute</u> = 29.92 in-Hg <u>absolute</u>). Recall that vacuum pressure starts measurement at the local atmospheric pressure and is measured down from there. The absolute pressure in in-Hg is measured from absolute zero pressure and is the difference between atmospheric pressure and the gage pressure:
    (29.92 – 27.88) in-Hg = 2.04 in-Hg absolute x (29.92 in-Hg / 14.7 psi) = 1 psia.
    [NOTE – Round off to the nearest tenth and then, if it is a low pressure not listed on Sat Steam Pressure Table, <u>then look for it on column 2 of Sat Steam Temperature Table</u>.]



p_{low} = 1.0 psia

b. p_{high} = 600 psia (given). Since no info is given about the pressure drops through the heat exchangers, then utilize to the "isobaric heat exchanger simplification."

3. Determine T_{sat} for the pressures. These are needed for graphing on the *T*-*s* graph and for determining which steam table to use.

   a. T_{sat} (1 psia) = 101.7 ^{o}F

   b. T_{sat} (600 psia) = 486.2 ^{o}F

4. Analyze and fill in the other "givens."

   a. $T_{turbine\ inlet} = T_3$ = 500 ^{o}F

5. Complete the rest of the table in this sequence.

   a. $T_1 = T_{sat}$ - Condensate Depression = 101.7 – 3.7 = 98.0 ^{o}F

   b. $h_1 = h_f$ (98 ^{o}F) = 66.041 Btu/lbm [Note: Uses the CL Approx technique]

   c. $v_1 = v_f$ (98 ^{o}F) = 0.016125 ft^3/lb$_m$ [Note: CL Approx technique]

   d. $w_{p,s} = v_f\, \Delta p = h_{2s} - h_1$ = (0.016125 ft^3/lb$_m$)(600-1 lb$_f$/in^2)(144in^2/ft^2)(1Btu/778 ft-lb$_f$)

      $w_{p,s}$ = 1.79 Btu/lb$_m$

      $h_{2s} = h_1 + wk_{p,s}$ = 66.041 + 1.79 = 67.82 Btu/lb$_m$

   e. p_2 = 600 psia [This is on the high pressure isobar line]

   f. $T_{2s} = T_{sat}\ (h_f$ = 67.82) = 99.78 ^{o}F [NR; CL Approx; interpolate using h_f on Table 1]

      {Alternatively $\Delta h = c_p\, \Delta T$; c_p = 1.0 Btu/lb$_m$-^{o}R and assuming constant specific heat, then $\Delta h = \Delta T$: ΔT_s = 1.79 ^{o}F ; T_{2s} = 98 + 1.79 = 99.79 ^{o}F}

   g. $\eta_p = (h_{2s} - h_1) / (h_2 - h_1) = w_{p,s} / (h_2 - h_1)$
      $h_2 = [(h_{2s} - h_1) / \eta_p] + h_1$ = [1.79 / 0.8] + 66.041 = 68.28 Btu/lb$_m$

   h. $w_{p,real} = (h_{2s} - h_1) / \eta_p$ = 1.79 / 0.8 = 2.24 Btu/lb$_m$ [NR – You have it as Δh]
      $T_2 = T_{sat}\ (h_f$ = 68.28) = 100.2 ^{o}F [NR; CL Approx; interpolated using h_f on Table 1 or by alternate method in 5.f]

   i. $h_{2'} = h_f$(600 psia) = 471.7 Btu/lb$_m$

   j. $h_3 = h$(600 psia, 500 ^{o}F) = 1216.5 Btu/lb$_m$

   k. $s_3 = s$(600 psia, 500 ^{o}F) = 1.4597 Btu/lb$_m$-^{o}R

   l. $s_{4s} = s_3$ = 1.4597 Btu/lb$_m$-^{o}R

m. $x_{4s} = [s_{4s} - s_f\,(1\text{ psia})] / s_{fg}\,(1\text{ psia}) = [1.4597 - 0.1326] / 1.8450 = 0.719$ (71.9%)

n. $x_{4s} = [h_{4s} - h_f\,(1\text{ psia})] / h_{fg}\,(1\text{ psia})$
$h_{4s} = [x_{4s} * h_{fg}\,(1\text{ psia})] + h_f\,(1\text{ psia}) = [0.719 * 1035.7] + 69.73 = 814.7$ Btu/lb_m

o. $\eta_T = (h_3 - h_4) / (h_3 - h_{4s})$

$h_4 = h_3 - \eta_T\,(h_3 - h_{4s}) = 1216.5 - 0.9\,(1216.5 - 814.7) = 854.9$ Btu/lb_m

p. $x_4 = [h_4 - h_f\,(1\text{ psia})] / h_{fg}\,(1\text{ psia}) = [854.9 - 69.73] / 1035.7 = 0.758$ (75.8%)

q. T_{4s} and T_4 are both T_{sat} (1 psia) = 101.7 ^{o}F because they are in the WV region. [NR]

The State Point Table is now complete (as complete as it needs to be to fill out the enthalpy row).

6. Answer the problem's other questions. In this case – η_{th}; $q_{Economizer}$:

a. $\eta_{th} = w_{net} / q_s = (w_T - w_p) / qs = [(h_3 - h_4) - (h_2 - h_1)] / (h_3 - h_2)$

$\eta_{th} = [(1216.5 - 854.9) - (2.24)] / (1216.5 - 66.04) = 0.312 = 31.2\%$

b. $q_{Economizer} = h_{2'} - h_2 = 471.7 - 68.3 = 403.4$ Btu/lb_m

Final Answers

$x_{Turbine\ \ Discharge} = x_{4,\,\underline{real}} = 75.8\%$

Notice that this is at the <u>real</u> discharge (and not at the isentropic discharge conditions)!

$\eta_{th} = 31.2\%$

$q_{Economizer}$ = 403.4 Btu/lb_m

Notice that the rest of the boiler adds about 745 Btu/lb_m to the working fluid in this problem. The Economizer adds a significant amount of heat and this heat came from stack gases that were just going to be "thrown away." The economizer significantly increases the efficiency of the boiler and the overall steam plant.

<u>Unit Definitions</u>. Sometimes knowing how the unit was established helps the students to remember and appreciate the magnitude of the term.

- A British thermal unit (Btu) is analogous to a calorie in SI and is defined as the heat energy necessary to raise the temperature of one pound of cool water by one degree Fahrenheit.
- A ton of refrigeration capacity was established as the amount of heat absorbed by melting a short ton (2000 pounds) of ice at 32 ^{o}F to water at 32 ^{o}F. This is the latent heat of fusion and considered on an hourly basis in the AC&R industry as 12,000 Btu/hr.
- Horsepower. Steam engine developer, James Watt (1736-1819) did not originate the term "horsepower," but he did standardize it. He used the unit to market his steam engines as the number of horses one of his engines would replace. Watt determined that a horse could turn a 12-foot radius bar (driving a mill wheel) 144 times per hour or 2.4 RPM. The horse traveled $(2\,\pi)\,(12)$[ft/rev] (2.4) [rev/min] or 180 ft in 1 minute. Watt measured the pulling force on the bar at 180 lbf, so $\dot{W}$ (1 horse) = (F) (d/t) = (180 lbf) (180 ft/min) =

32,555 ft-lbf/min. Watt rounded this to 33,000 ft-lbf/min and we use that conversion factor to this day.[19]

Conclusion

Americans continue to use a variety of unit systems, some based on the United States Customary System of units, some based on specific industry or trade conventions, and some based on the SI system. The advance of metrication in the United States still has a long way to go, even though academe teaches predominately in SI. Personnel re-training costs, fear of expensive mishaps during transitions, the large preponderance of legacy systems and equipment utilizing customary units on their gages and other instruments in industry, and the intransigence of the American people, all contribute to maintaining these traditional, non-SI unit systems, regardless of the education system.

Since the majority of engineering graduates go to work for employers who use other unit systems, then it is incumbent upon engineering educators to assist our graduates in developing the skillsets that will be most beneficial in obtaining employment and making an early contribution to their new employers without requiring significant re-training. One such skillset is reasonable proficiency in unit analysis, the unique attributes of the USCS system of units, and the unit systems customarily used in specific trades and industrial applications in which they may find employment.

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[3] Encyclopedia Britannica, keyword "grain."
[4] http://www.npl.co.uk/educate-explore/factsheets/history-of-length-measurement/history-of-length-measurement, accessed 1/2/2014.
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[18] Benderly (2013), p. 32.
[19] Wikipedia, "horsepower" 1/19/10.