Elementary thermodynamics

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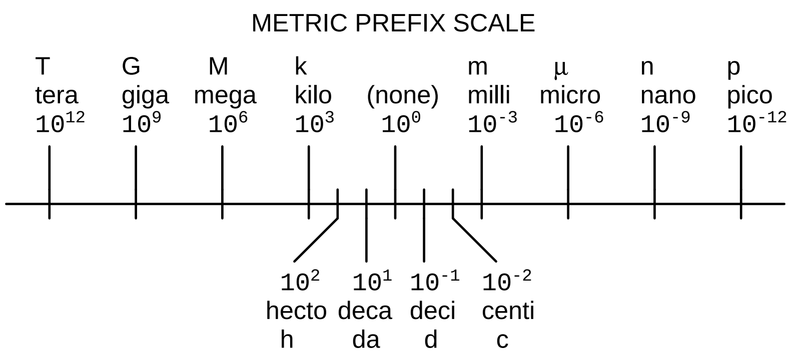
Metric prefixes and conversion constants

- **Metric prefixes**
- Yotta = 10^{24} Symbol: Y
- Zeta = 10^{21} Symbol: Z
- Exa = 10^{18} Symbol: E
- Peta = 10^{15} Symbol: P
- Tera = 10^{12} Symbol: T
- Giga = 10^{9} Symbol: G
- Mega = 10^{6} Symbol: M
- Kilo = 10^{3} Symbol: k
- Hecto = 10^{2} Symbol: h
- Deca = 10^{1} Symbol: da
- Deci = 10^{-1} Symbol: d
- Centi = 10^{-2} Symbol: c
- Milli = 10^{-3} Symbol: m
- Micro = 10^{-6} Symbol: μ
- Nano = 10^{-9} Symbol: n
- Pico = 10^{-12} Symbol: p
- Femto = 10^{-15} Symbol: f
- Atto = 10^{-18} Symbol: a
- Zepto = 10^{-21} Symbol: z
- Yocto = 10^{-24} Symbol: y



- **Conversion formulae for temperature**
- ^{o}F = (^{o}C)(9/5) + 32
- ^{o}C = (^{o}F - 32)(5/9)
- ^{o}R = ^{o}F + 459.67
- K = ^{o}C + 273.15

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

1 gallon (gal) = 231.0 cubic inches (in^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm^3)

Conversion equivalencies for velocity

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot – international)

Conversion equivalencies for mass

1 pound (lbm) = 0.45359 kilogram (kg) = 0.031081 slugs

Conversion equivalencies for force

1 pound-force (lbf) = 4.44822 newton (N)

Conversion equivalencies for area

1 acre = 43560 square feet (ft^2) = 4840 square yards (yd^2) = 4046.86 square meters (m^2)

Conversion equivalencies for common pressure units (either all gauge or all absolute)

1 pound per square inch (PSI) = 2.03602 inches of mercury (in. Hg) = 27.6799 inches of water (in. W.C.) = 6.894757 kilo-pascals (kPa) = 0.06894757 bar

1 bar = 100 kilo-pascals (kPa) = 14.504 pounds per square inch (PSI)

Conversion equivalencies for absolute pressure units (only)

1 atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilo-pascals absolute (kPaA) = 1.01325 bar (bar) = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

Conversion equivalencies for energy or work

1 british thermal unit (Btu – "International Table") = 251.996 calories (cal – "International Table") = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10^{10} ergs (erg) = 778.169 foot-pound-force (ft-lbf)

Conversion equivalencies for power

1 horsepower (hp – 550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (Btu/hr) = 0.0760181 boiler horsepower (hp – boiler)

Acceleration of gravity (free fall), Earth standard

9.806650 meters per second per second (m/s^2) = 32.1740 feet per second per second (ft/s^2)

Physical constants

Speed of light in a vacuum (c) = 2.9979×10^8 meters per second (m/s) = 186,281 miles per second (mi/s)

Avogadro's number (N_A) = 6.022×10^{23} per mole (mol^{-1})

Electronic charge (e) = 1.602×10^{-19} Coulomb (C)

Boltzmann's constant (k) = 1.38×10^{-23} Joules per Kelvin (J/K)

Stefan-Boltzmann constant (σ) = 5.67×10^{-8} Watts per square meter-Kelvin^4 ($W/m^2 \cdot K^4$)

Molar gas constant (R) = 8.314 Joules per mole-Kelvin (J/mol-K)

Properties of Water

Freezing point at sea level = 32^oF = 0^oC

Boiling point at sea level = 212^oF = 100^oC

Density of water at 4^oC = 1000 kg/m^3 = 1 g/cm^3 = 1 kg/liter = 62.428 lb/ft^3 = 1.94 $slugs/ft^3$

Specific heat of water at 14^oC = 1.00002 calories/g$\cdot^o$C = 1 BTU/lb$\cdot^o$F = 4.1869 Joules/g$\cdot^o$C

Specific heat of ice $\approx$ 0.5 calories/g$\cdot^o$C

Specific heat of steam $\approx$ 0.48 calories/g$\cdot^o$C

Absolute viscosity of water at 20^oC = 1.0019 centipoise (cp) = 0.0010019 Pascal-seconds (Pa$\cdot$s)

Surface tension of water (in contact with air) at 18^oC = 73.05 dynes/cm

pH of pure water at 25^o C = 7.0 (*pH scale = 0 to 14*)

Properties of Dry Air at sea level

Density of dry air at 20^oC and 760 torr = 1.204 mg/cm^3 = 1.204 kg/m^3 = 0.075 lb/ft^3 = 0.00235 $slugs/ft^3$

Absolute viscosity of dry air at 20^oC and 760 torr = 0.018 centipoise (cp) = 1.8×10^{-5} Pascal-seconds (Pa$\cdot$s)

file `conversion_constants`

Question 1

Saturated Steam Table

Temperature (Deg F)	Pressure (PSIA)	Sensible heat of liquid (BTU/lb)	Latent heat of vapor (BTU/lb)	Total heat (BTU/lb)
32	0.0886	0.00	1073.4	1073.4
40	0.1217	8.05	1068.9	1076.9
50	0.1780	18.08	1063.3	1081.4
60	0.2562	28.08	1057.8	1085.9
70	0.3626	38.06	1052.3	1090.3
80	0.505	48.03	1046.7	1094.8
90	0.696	58.00	1041.2	1099.2
100	0.946	67.97	1035.6	1103.6
110	1.271	77.94	1030.0	1108.0
120	1.689	87.91	1024.4	1112.3
130	2.219	97.89	1018.8	1116.7
140	2.885	107.87	1013.1	1121.0
150	3.714	117.86	1007.4	1125.3
160	4.737	127.86	1001.6	1129.5
170	5.992	137.87	995.8	1133.7
180	7.51	147.88	989.9	1137.8
190	9.34	157.91	983.9	1141.8
200	11.52	167.94	977.8	1145.8
210	14.13	177.99	971.6	1149.6
212	14.70	180.00	970.4	1150.4
220	17.19	188.1	965.2	1153.3
230	20.77	198.2	958.7	1156.9
240	24.97	208.3	952.1	1160.4
250	29.82	218.5	945.3	1163.8
260	35.42	228.6	938.4	1167.0
270	41.85	238.8	931.4	1170.2
280	49.18	249.0	924.3	1173.3
290	57.55	259.3	916.9	1176.2
300	67.00	269.6	909.5	1179.1
310	77.67	279.9	901.9	1181.8
320	89.63	290.2	894.2	1184.4
330	103.0	300.6	886.3	1186.9
340	118.0	311.0	878.3	1189.3
350	134.6	321.4	870.1	1191.5
360	153.0	331.9	861.8	1193.7
370	173.3	342.4	853.4	1195.8
380	195.6	352.9	844.8	1197.7
390	220.2	363.5	836.1	1199.6
400	247.1	374.1	827.2	1201.3
410	276.4	384.7	818.2	1202.9
420	308.4	395.4	809.0	1204.4
430	343.2	406.2	799.6	1205.8
440	380.8	417.0	790.1	1207.1

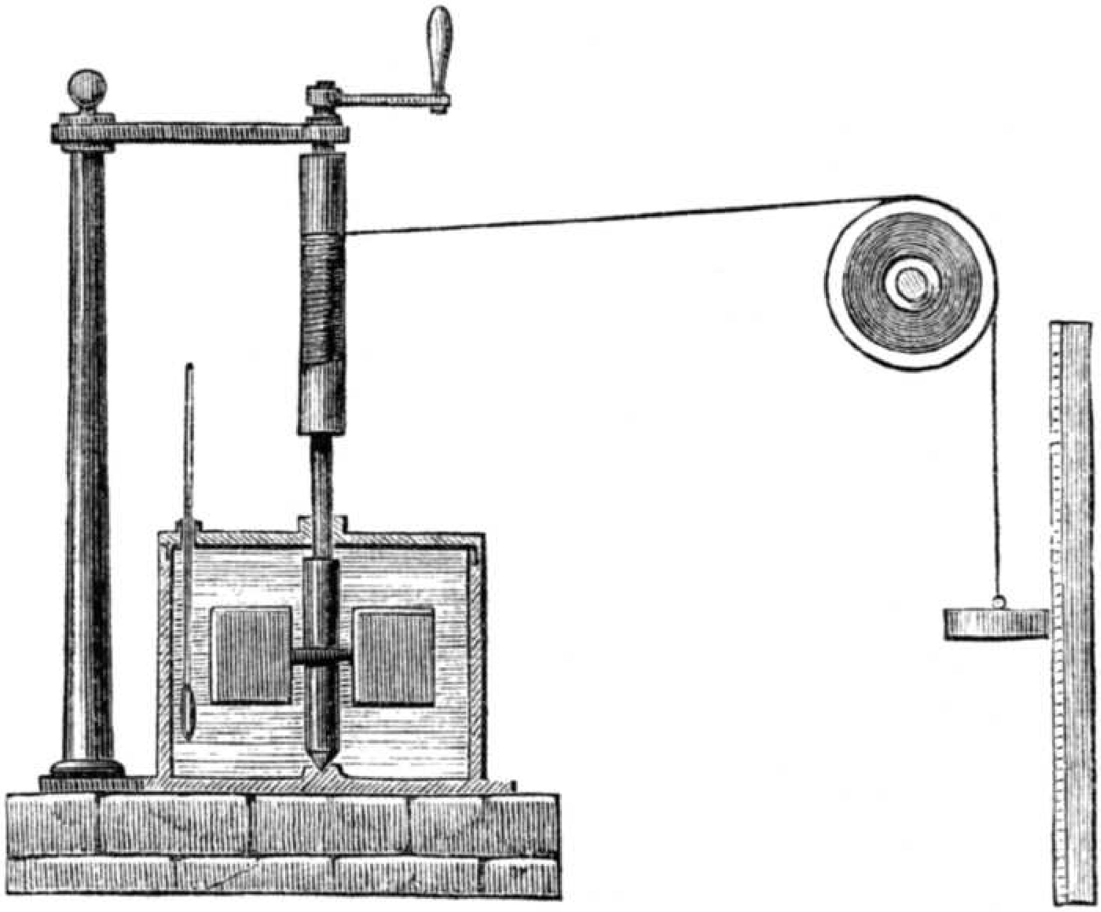
Saturated Steam Table (continued)

Temperature (Deg F)	Pressure (PSIA)	Sensible heat of liquid (BTU/lb)	Latent heat of vapor (BTU/lb)	Total heat (BTU/lb)
450	422	428	780	1208
460	466	439	770	1209
470	514	450	760	1210
480	565	462	749	1211
490	620	473	738	1211
500	679	484	727	1211
510	743	496	715	1211
520	810	507	703	1210
530	883	519	690	1209
540	960	531	677	1208
550	1043	542	664	1206
560	1130	554	650	1204
570	1224	566	635	1201
580	1323	578	619	1197
590	1428	591	602	1193
600	1540	604	585	1189

file i00872

Question 2

In the mid 1800's, James Prescott Joule performed an experiment demonstrating how mechanical energy could be converted into heat. His experimental apparatus is shown in this illustration, taken from issue 231 of *Harper's New Monthly Magazine* in August of 1869:



Examine this mechanism and then explain how it functions. Specifically, what data would the experimenter record when running the experiment, and how would this data be used to establish a relationship between mechanical energy and heat?

file i02768

Question 3

In 1804, an experimenter named Sir Benjamin Thompson (also known as Count Rumford) investigated the heat liberated from the mechanical boring of the hole in a newly manufactured cannon. The cannon barrel was immersed in a box full of water for cooling, and by using a dull tool to bore the hole in the cannon Thompson was able to prolong the process of boring until he had generated enough heat to actually boil the water contained in the box.

A popular theory of heat at this time was the so-called *caloric theory*, which maintained that heat was an invisible fluid called "caloric" that could be passed from one object to another by direct contact. According to the caloric theory, the reason a new cannon barrel became hot during the process of boring a hole in it was because the cleaving of metal chips from the barrel by a sharp tool released some of the caloric "fluid" stored within the metal.

Albert Einstein was reported to have quipped, *No amount of experimentation can can ever prove me right; a single experiment can prove me wrong.* The truth in this statement is that science does not validate some claims so much as it *invalidates* other claims – the power of scientific experimentation being in the *disproof* rather than in the *proof*. A theory may be overthrown if one or more of its testable predictions proves to be false.

Apply this strategy to testing the caloric theory of heat (that heat is an invisible fluid released by cutting metal) in Thompson's cannon-boring experiment. Does the caloric theory pass this test, or not? Explain your answer in detail.

file i04779

Question 4

The concepts of *sensible heat* and *latent heat* are often confusing to people first studying thermodynamics. Do your best to differentiate between these two heat-transfer phenomena, and give practical examples of each.

Additionally, express any mathematical formulae relevant to sensible heat and to latent heat.

file i04775

Question 5

The three major mechanisms of heat transfer are *conduction*, *convection*, and *radiation*. Give practical examples for each of the following phenomena:

- *Conductive* transfer resulting in *sensible* heat
- *Convective* transfer resulting in *sensible* heat
- *Radiant* transfer resulting in *sensible* heat
- *Conductive* transfer resulting in *latent* heat
- *Convective* transfer resulting in *latent* heat
- *Radiant* transfer resulting in *latent* heat

Additionally, express any mathematical formulae relevant to sensible versus latent heat.

file i04776

Question 6

A block of iron and a block of copper are both heated to 200^o F in an oven, then placed on a wooden table to cool down to room temperature. Assuming all other factors being equal (mass, surface area, etc.), which block will cool at a faster rate? Why??

file i00330

Question 7

Suppose you need to heat up the 70 gallons of water filling the inside of a hot tub, from ambient temperature (58 ^{o}F) to 102 ^{o}F. Assuming a perfectly insulated hot tub, and ignoring the thermal mass of the hot tub frame itself, how much thermal energy (in units of BTU) will be needed to raise its temperature to the desired operating point?

file i01010

Question 8

Jane has an ear ache, and decides to apply a hot water bottle to her ear to help loosen the congestion in her ear canals and ease the pain. Being a pre-med student who recently studied thermodynamics, she estimates a heat input of 19,000 calories necessary to do the job.

Assuming Jane's hot water tap provides water at a temperature of 54 degrees Celsius and that her skin temperature is about 31 degrees Celsius, calculate how much water Jane will need to put into her hot water bottle to deliver the estimated amount of heat to her head as the bottle cools from its initial hot-water temperature down to her skin temperature.

Also, determine if your calculated value is a *high* estimate or a *low* estimate, based on simplifications assumed in your calculations.

file i01011

Question 9

While on a camping trip, Sally needs to collect enough firewood to fuel a campfire that will bring 5 gallons of water to a boil. Assuming a heat of combustion value of 9000 BTU per pound of dry wood, how much wood must Sally collect for the fire that will heat this water? Assume that the ambient air temperature is 51 degrees F, and that the boiling point of water at Sally's altitude is 205 degrees F.

file i00408

Question 10

15 grams of iron filings at a temperature of 150 ^{o}C are sprinkled onto a 25 gram strip of copper metal at room temperature (20 ^{o}C), and left to equalize in temperature inside of a perfectly insulated chamber. Calculate the final temperature of the iron/copper mass.

file i01013

Question 11

A dough-making process at an industrial bakery mixes hot water into an insulated vessel along with ground wheat flour. Other ingredients are added to this mix, but flour and water are by far the largest constituents.

Calculate the final temperature of the dough, assuming the following quantities:

- Mixing vessel is made of steel ($c = 0.12$ BTU/lb-^{o}F) weighing 22 pounds, initially at 60 ^{o}F
- 75 pounds of wheat flour ($c = 0.43$ BTU/lb-^{o}F), initially at 60 ^{o}F
- 180 pounds of water ($c = 1.0$ BTU/lb-^{o}F), initially at 120 ^{o}F

file i01012

Question 12

Rank the following transitions according to the amount of heat energy input required:

- To heat a pound of water from 60^o F to 65^o F.
- To boil a pound of water completely into steam (warming it from 211^o F to 213^o F).
- To melt a pound of ice completely into water (warming it from 31^o F to 33^o F).

Suggestions for Socratic discussion

- Which of these transitions involves *sensible heat* and which involve *latent heat*?

file i00353

Question 13

Suppose exactly 1000 calories of heat energy is transferred to a 5-gram mass of water at 20^o C and at atmospheric pressure (sea level). Calculate what will happen to the water (how far will its temperature be raised, and if it boils, how much steam will be liberated from the water?).

Hint: the specific heat of water is 1 calorie/gram-C^o. The latent heat of fusion for water is 80 calories/gram, and the latent heat of vaporization for water is 540 calories/gram.
file i01796

Question 14

Calculate the amount of heat energy released by two pounds of superheated steam (at atmospheric pressure) as it cools from 400 ^{o}F to 125 ^{o}F, in units of BTU. Be sure to separate your solution into three steps: the heat lost as the steam cools to the condensing temperature (212 ^{o}F), the latent heat released through condensation, and the heat lost as the condensed water cools to the final temperature of 125 ^{o}F.

In which step of this three-step heat loss process is *most* of the heat being released? What does this indicate about the heat-storing capabilities of water, steam, and phase changes between water and steam?

Next, use numbers taken from a *steam table* to calculate the same heat release: subtracting the enthalpy (also known as *total heat*, or h) of 400 ^{o}F steam from the enthalpy of 125 ^{o}F water. Assume the steam is at atmospheric pressure. How closely does this calculated value agree with your previous calculation?

Hint: the *Socratic Instrumentation* website contains a page where you may download public-domain textbooks, one of which is a set of steam tables published in 1920.

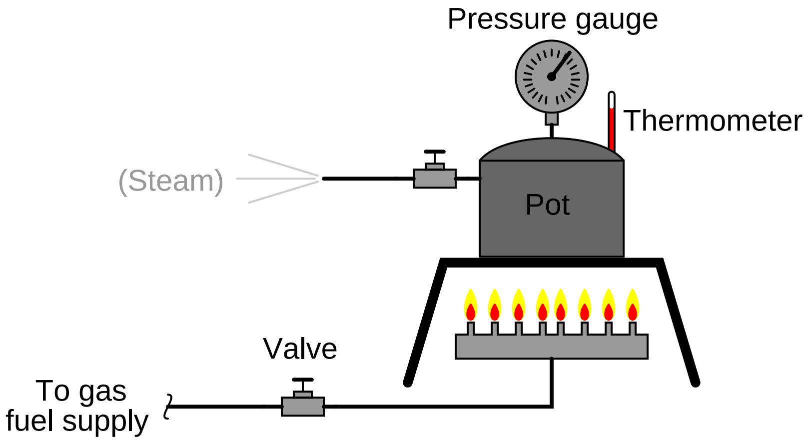
Suggestions for Socratic discussion

- Be sure to discuss how to properly use a steam table to reference enthalpy values.
- Some superheated steam tables index their entries by the "total" temperature of the steam, while others list the amount of "superheat." What exactly does *superheat* mean, and how do we calculate it?
- Which result do you think is more accurate: the one calculated in three steps, or the one calculated from steam table enthlapy?

file i03982

Question 15

A student, weary of performing "thought experiments," decides to perform a *real* experiment to better understand phase changes. She assembles a primitive steam boiler using a pressure cooker, a pressure gauge, a thermometer, a couple of valves, and a burner as a source of heat:



Her hypothesis is that boiler temperature may be controlled by fuel gas flow (burner heat rate output), and that boiler pressure may be controlled by steam flow out of the boiler. Two process measurements, and two control valves: what could be simpler?

However, the student soon discovers that she cannot *independently* control boiler pressure and boiler temperature. When fuel flow is increased, *both* pressure and temperature rise; as the steam valve is opened, *both* pressure and temperature decrease.

Explain why this experiment did not go as planned, and what important lesson this student should learn about phase changes.

file i01795

Question 16

Suppose a process vessel containing only H_2O is equipped with both a temperature indicator and a pressure indicator. Consult a *steam table* to determine whether the conditions within this vessel are *water only*, *water and steam mixed*, or *steam only*:

- T = 501 ^{o}F and P = 810 PSIG
- T = 250 ^{o}F and P = 75 PSIG
- T = 690 ^{o}F and P = 1886 PSIG
- T = 369 ^{o}F and P = 550 PSIG
- T = 274 ^{o}F and P = 30 PSIG
- T = 471 ^{o}F and P = 405 PSIG

If you determine the process condition to be *steam only*, calculate the amount of superheat (i.e. the number of degrees F that the steam is heated beyond the boiling temperature).

Hint: the *Socratic Instrumentation* website contains a page where you may download public-domain textbooks, one of which is a set of steam tables published in 1920.

Suggestions for Socratic discussion

- Plot where each of these temperature/pressure points falls on a *phase diagram* for ice, water, and steam.

file i00347

Question 17

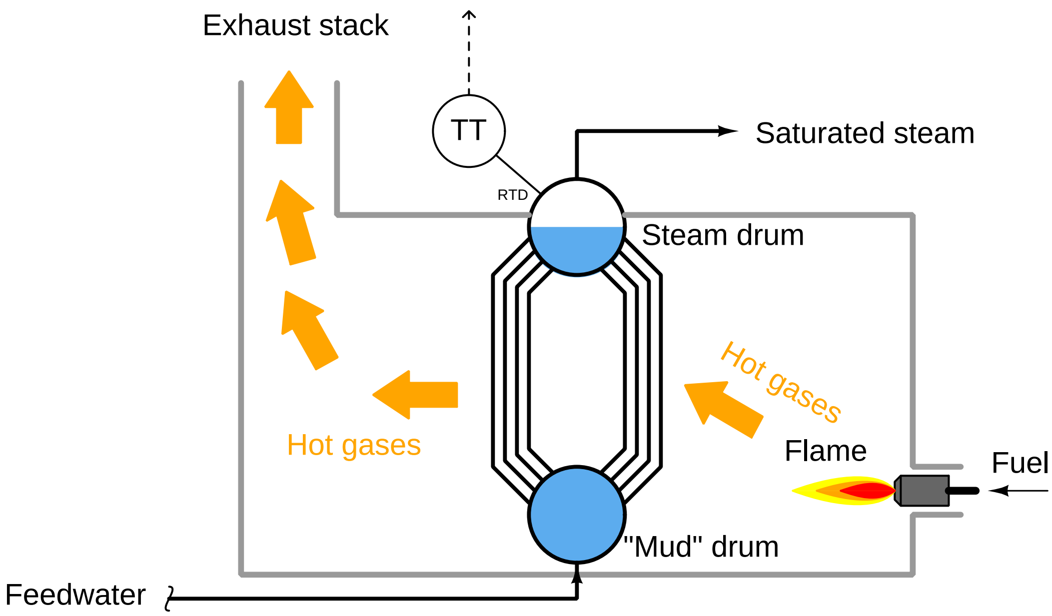
Suppose a steam boiler is supposed to have a capacity of 300 pounds (of steam) per hour. How much heat energy (in BTUs per hour) will it take to boil this rate of steam, assuming that water enters the boiler at 212 ^{o}F?

Hint: the specific heat of water is 1 BTU/lb_m-F^o. The latent heat of fusion for water is 144 BTU/lb_m, and the latent heat of vaporization for water is 970 BTU/lb_m.

file i01797

Question 18

The following steam boiler takes in purified "feed" water and heats it up to become steam, using the energy of natural gas fuel:



Supposing the feedwater's temperature is 63 ^{o}F and the steam drum pressure is 232 PSIG, determine the temperature of the saturated steam as well as the amount of heat energy (in BTU) absorbed by every pound of feedwater as it passes through the boiler and becomes steam.

$T_{steam} =$ ________ ^{o}F

$Q =$ ________ BTU per pound

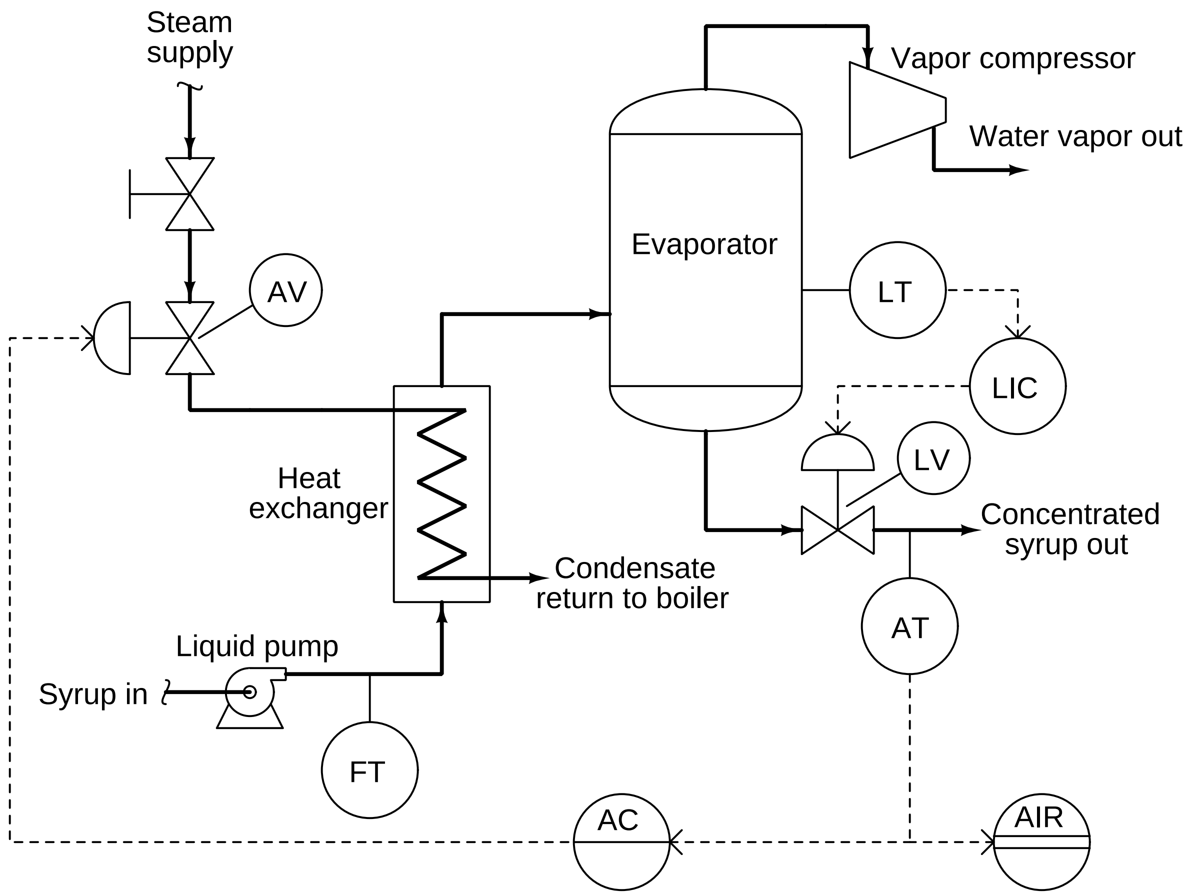
Supposing the feedwater flow rate is 20 pounds per minute, calculate the *rate* of heat absorbed by the feedwater by the burner's flame:

$\frac{dQ}{dt} =$ ________ BTU per minute

file i02714

Question 19

Steam is used in the following process to heat up raw maple syrup as part of the evaporation process:



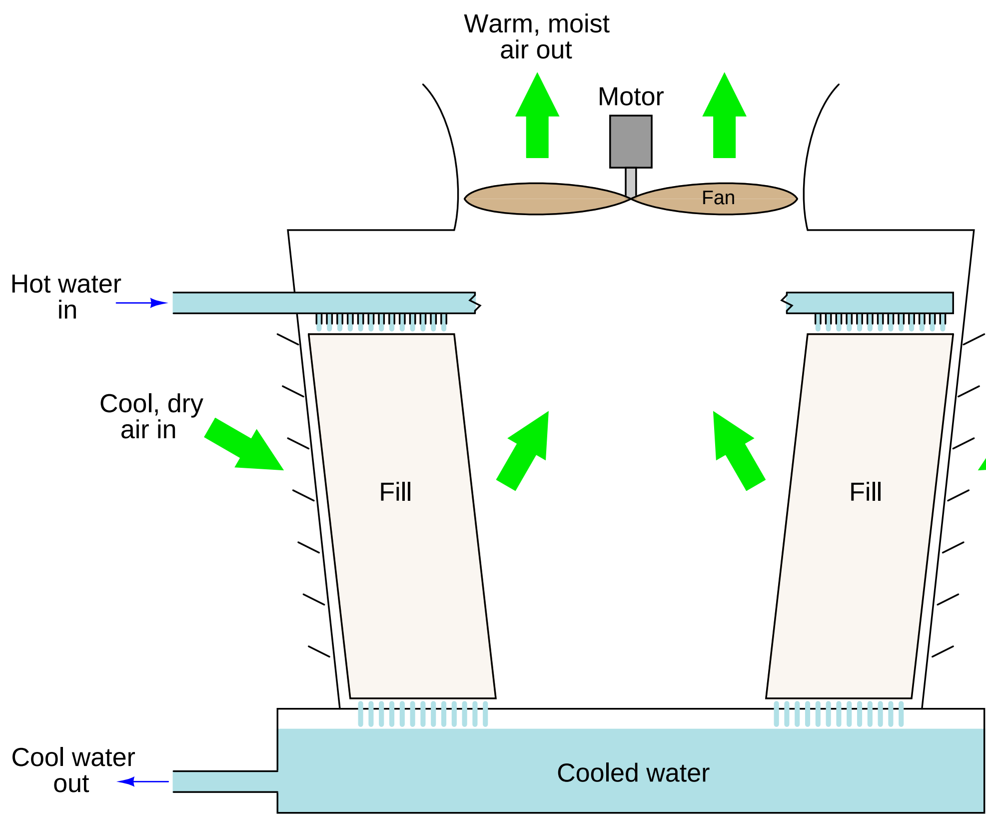
The raw maple syrup enters the heat exchanger having a specific heat value (c) of 0.95 and a mass flow rate of 12 pounds per minute. Calculate the rate of steam flow necessary to raise the temperature of this syrup from 57 ^{o}F to 210 ^{o}F if the steam enters the exchanger in a saturated condition at 300 ^{o}F and leaves as hot water at 130 ^{o}F.

Steam flow rate = __________ pounds per minute

file i02715

Question 20

An evaporative cooling tower cools off water by mechanically forcing some of it into a vapor state. As that portion of the hot water turns into vapor, the latent heat of vaporization is drawn from the remaining liquid water, forcing it to decrease in temperature (i.e. the liquid water loses sensible heat in order to supply the vapor with latent heat):



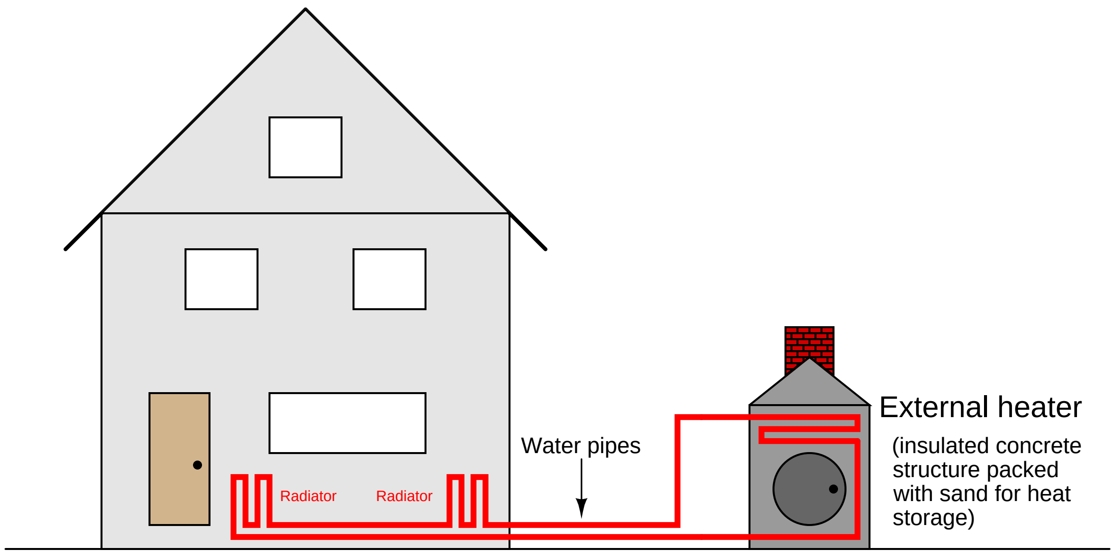
Suppose 1000 pounds of hot water enters the cooling tower at a temperature of 137 ^oF. 50 pounds of this water becomes vaporized, leaving the tower at a temperature of 111 ^oF. The remaining liquid water exiting the tower will be at some cooler temperature.

Calculate how many pounds of water exit the tower for the 1000 pounds that entered. Then, calculate the temperature of that cooled water. Note: in all these calculations we will ignore any heat energy carried away by air flowing through the tower, since this will be a small quantity compared to the heat carried away by the vapor and by the liquid water exiting the tower.

file i02631

Question 21

A type of heating system developed to provide a measure of safety and convenience for self-sufficient homes is an *external heater*, where fuel such as wood is burned at high temperature for short durations in an outdoor furnace, and the heat from that furnace stored in a large "thermal reservoir" of sand. A fire is lit inside the furnace only once every few days, then the heat from that burn is transferred to the home by means of water pumped through heat exchangers:



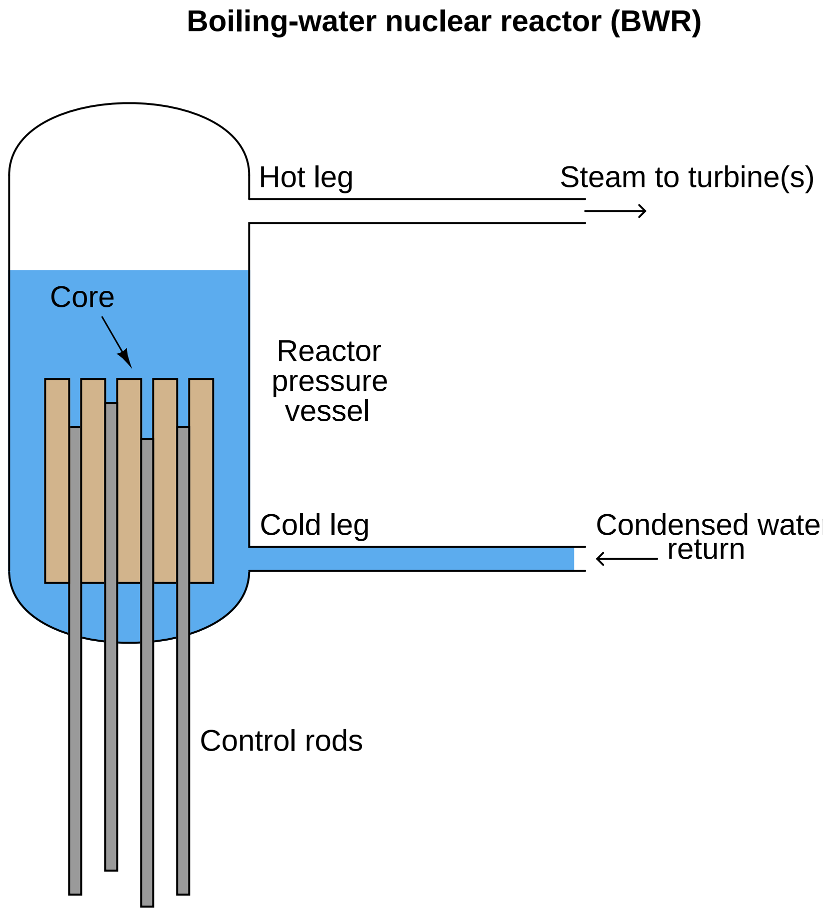
Answer the following questions about this type of heating system:

- What advantages might there be with this design versus a furnace installed inside the home?
- Why is *sand* a good choice as a heat-storage medium inside the furnace structure?
- Is the heat storage in this system based on *specific heat* or *latent heat*?
- Is the heat transfer in this system (from heater to home) based on *specific heat* or *latent heat*?
- How may the home's temperature be thermostatically controlled?
- How to equip the system with an alarm prompting the user to light a new fire in the furnace?
- Calculate the enthalpy of the water as it enters the home (from the heater) at a temperature of 184 ^{o}F.
- Calculate the enthalpy of the water as it leaves the home (on its way to the heater) at a temperature of 127 ^{o}F.
- Calculate the rate of heat delivered to the home by this hot water assuming a water mass flow rate of 9.2 pounds per minute.

file i01017

Question 22

A *boiling-water reactor* (BWR) in a nuclear power plant uses the heat emitted by the nuclear "core" to boil water into steam, which is then used to turn a steam turbine and drive an electrical generator to produce electricity:



It is critically important that the nuclear core be kept completely submerged in water, lest it overheat.

Suppose the temperature and pressure measurements on a BWR are 780 ^{o}F and 495 PSIG, respectively. Reference a steam table and then determine whether the core is covered (submerged) or uncovered (exposed).

file i01018

Question 23

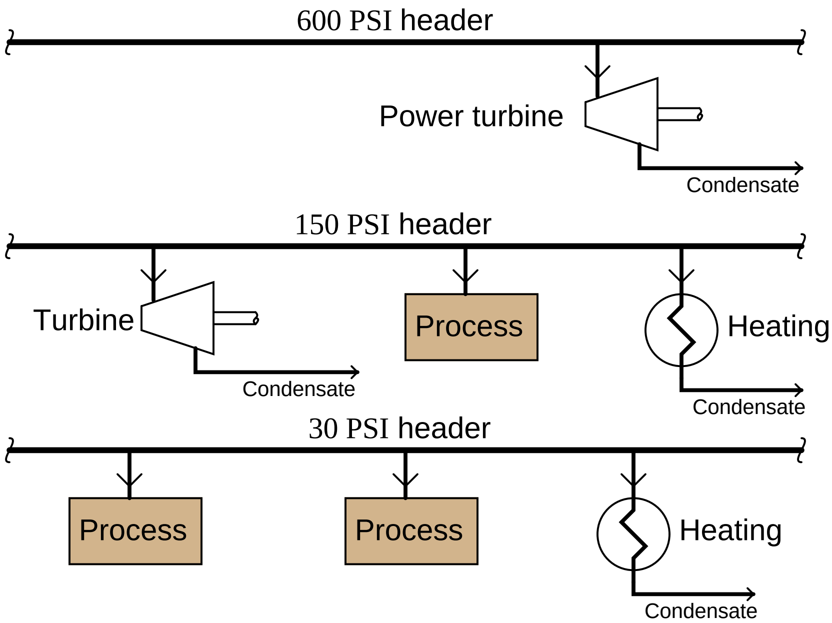
Suppose a steam turbine engine in a power plant receives steam from the boiler at a temperature of 583 ^{o}F and a pressure of 88 PSIG, and discharges steam at a temperature of 91 ^{o}F and a pressure of -14 PSIG. The mass flow rate of this steam is 2300 pounds per minute.

Assuming a turbine efficiency of 80%, calculate the mechanical power output by this steam turbine, in the unit of Watts.

file i02855

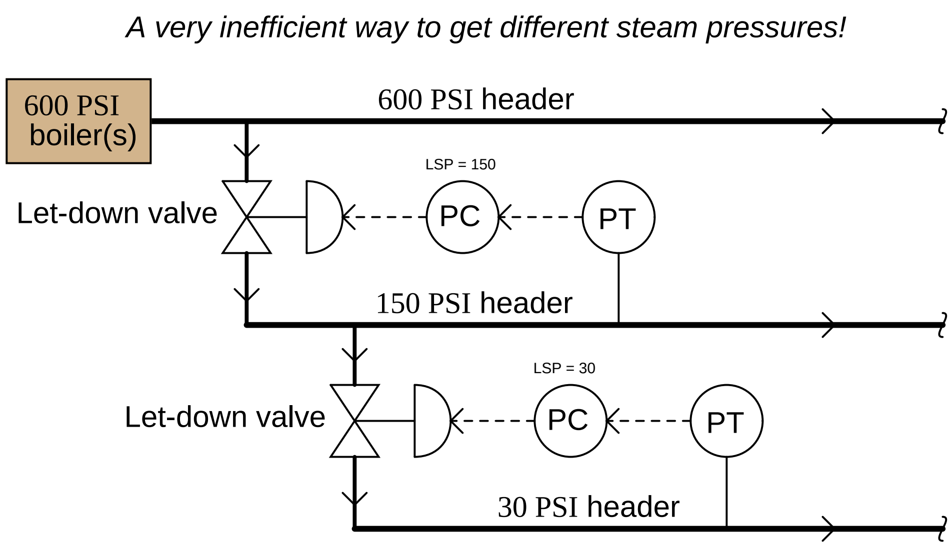
Question 24

Industrial operations using large quantities of steam often distribute it at different pressures, much like an electrical utility system distributing power at several different voltages:

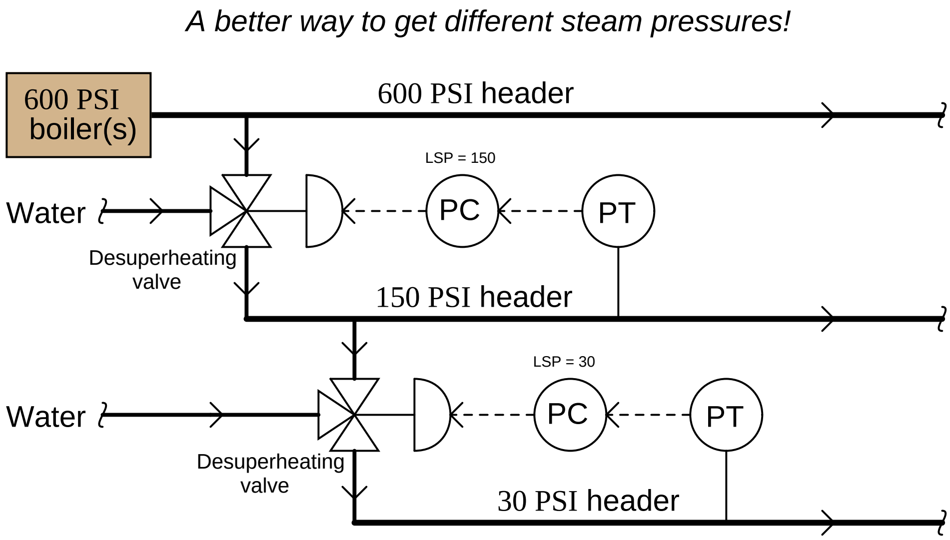


It may not always be practical to have a separate boiler (or set of boilers) for each header pressure (e.g. one boiler outputting 600 PSI, one outputting 150 PSI, and one outputting 30 PSI). So, often there is a need to "let down" high-pressure steam to a lower pressure.

Although it is possible to simply use control valves to throttle high-pressure steam into a lower-pressure headers, this would be a waste of energy. Such a strategy would be analogous to using resistive voltage dividers to step high voltage down to lower values in an electric power system:



An improvement over the plain let-down strategy is to use special *desuperheating* valves instead of normal throttling valves. Desuperheating is a process whereby water is sprayed into the throttled steam:



Desuperheaters may be thought of as the steam equivalent of electrical transformers: a much more efficient means of reducing pressure (voltage) than throttling with a restrictive (resistive) element. Explain how desuperheating works, and why the electrical transformer analogy is appropriate.

file i01801

Question 25

A construction trailer brought to an industrial job site during the winter measures 28 feet long by 8 feet high by 12 feet wide, having R-5 insulation in the walls, R-10 insulation in the ceiling, and R-7 insulation in the floor. Determine the necessary capacity of a heat source to maintain the interior temperature of this trailer at 75 ^{o}F while the outside temperature is 20 ^{o}F.

Heat rate = __________ BTU/hour

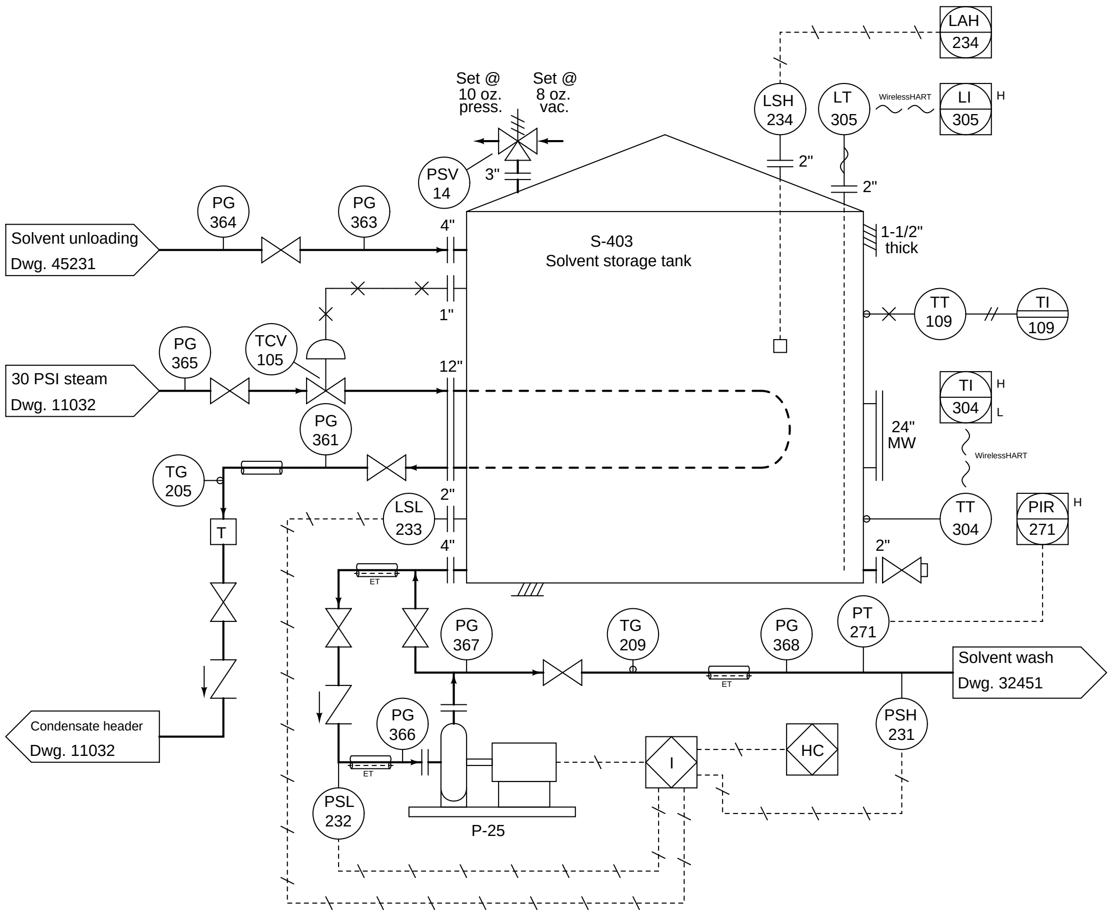
Suppose the heat source for this trailer is steam, supplied from a saturated steam line at 34.5 PSIG on the construction site. Steam enters the trailer through a high-temperature hose, then passes through a radiator where it heats air inside the trailer, and exits as hot water at 110 ^{o}F. Calculate the necessary flow rate of steam to maintain the trailer at 75 ^{o}F:

Steam flow rate = __________ lb/hour

file i02716

Question 26

Calculate the heat loss rate through the surfaces of this solvent storage tank, which is a vertical cylinder in shape. Assume the wall insulation has an R-value of 5 per inch of thickness, the floor insulation has an R-value of 2, and the roof insulation has an R-value of 4. The tank's diameter is 10 feet, its wall height is 13 feet, and its conical roof has a total surface area of 101 square feet. The setpoint for solvent temperature inside the tank is 95 degrees Fahrenheit, and the ambient air temperature is 40 degrees Fahrenheit:



Next, calculate the heat value rate of the fuel needed to fire this boiler, to keep the solvent tank temperature at setpoint. Assume a steam boiler efficiency (fuel heat value in, to heat delivered at the tank) of 83%.

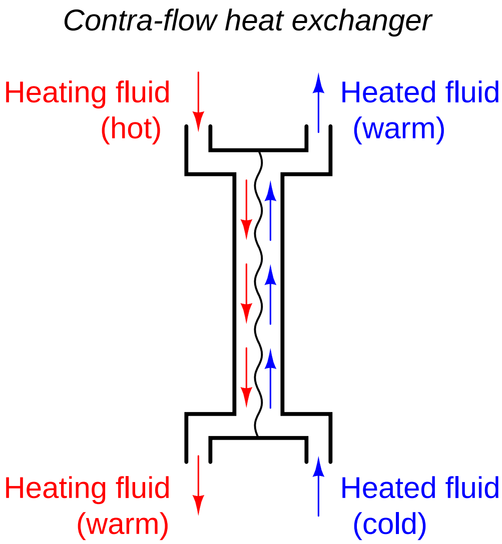
Suggestions for Socratic discussion

- Calculate the "lift" pressures of PSV-14 in units of inches water column.
- Explain the purpose of each protective interlock (safety switch) on the pump P-25 control system.

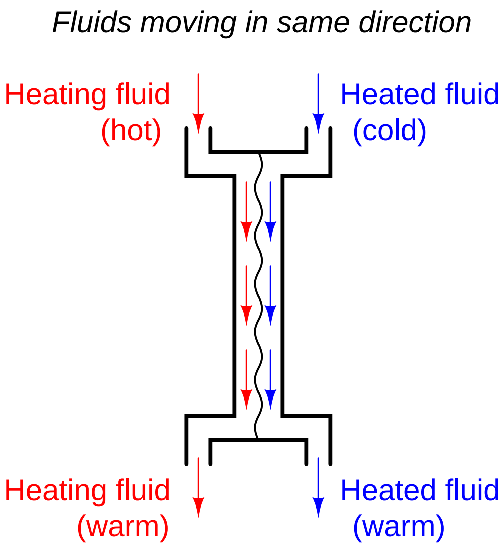
file i03485

Question 27

Steam heaters are almost always of the *contra-flow* design, where the two fluids pass by each other in opposing directions:



This is very intentional. If we were to have the fluids moving in the same direction, the exchanger would not be nearly as effective:



Explain why this is, making reference to the equation $\frac{dQ}{dt} = \frac{kA\Delta T}{l}$ if possible.
file i00335

Question 28

The rate of heat transfer through *radiation* from a warm body may be expressed by the Stefan-Boltzmann equation:

$$\frac{dQ}{dt} = e\sigma A T^4$$

Where,

$\frac{dQ}{dt}$ = Rate of heat flow

e = Emissivity factor

σ = Stefan-Boltzmann constant (5.67×10^{-8} W / m^2 $\cdot$ K^4)

A = Area of radiating surface

T = Absolute temperature

Based on the unit of measurement given for the Stefan-Boltzmann constant, determine the proper units of measurement for heat flow, emissivity, area, and temperature.

file i00343

Question 29

Solids tend to expand when heated. The amount a solid sample will expand with increased temperature depends on the size of the sample and the material it is made of. A formula expressing linear expansion in relation to temperature is as follows:

$$l = l_0(1 + \alpha\Delta T)$$

Where,

l = Length of material after heating
l_0 = Original length of material
α = Coefficient of linear expansion
ΔT = Change in temperature

Here are some typical values of α for common metals:

- Aluminum = 25×10^{-6} per degree C
- Copper = 16.6×10^{-6} per degree C
- Iron = 12×10^{-6} per degree C
- Tin = 20×10^{-6} per degree C
- Titanium = 8.5×10^{-6} per degree C

We may also express the tendency for the *area* and the *volume* of a solid to expand when heated, not just its linear dimensions. If we imagine a square with original length l_0 and original width l_0, the original area of the square must be ${l_0}^2$, which means the new area of the square after heating will be:

$$A = [l_0(1 + \alpha\Delta T)]^2$$

$$A = l_0^2(1 + \alpha\Delta T)^2$$

$$A = l_0^2(1 + \alpha\Delta T)(1 + \alpha\Delta T)$$

$$A = l_0^2[1 + 2\alpha\Delta T + (\alpha\Delta T)^2]$$

or

$$A = A_0[1 + 2\alpha\Delta T + (\alpha\Delta T)^2]$$

This equation may be simplified by approximation – a mathematical principle commonly applied in electrical engineering known as *swamping*:

$$A \approx A_0(1 + 2\alpha\Delta T)$$

Explain why it is okay to make this simplification, and extrapolate the principle to calculating the new *volume* of a solid material after heating.

file i00346

Question 30

Calculate the pressure of gas inside an enclosed vessel using the Ideal Gas Law, if the vessel volume is 1500 liters, the vessel and gas temperature is 125 ^{o}F, and the molecular quantity of gas inside the vessel is 80 moles. Express this pressure in units of atmospheres and also kPaG (kilopascals, gauge pressure).

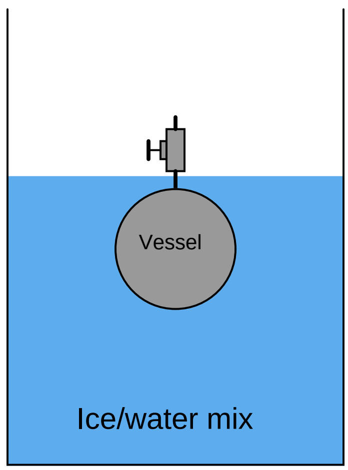
Suggestions for Socratic discussion

- The "Ideal Gas Law" is called *ideal* for a reason – it does not perfectly describe the behavior of real gases. Identify some scenarios where the Ideal Gas Law may yield erroneous results.

file i04014

Question 31

Suppose an empty test vessel of fixed volume is immersed in an ice-water mixture and allowed to stabilize at that temperature, with a bleed valve left open to equalize the vessel's air pressure with ambient (atmospheric) pressure at sea level:

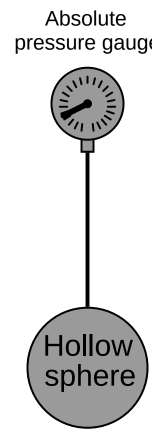


Once stabilized, the valve is shut off and the vessel is taken out of the ice-water bath, then left to stabilize at room temperature (70^o F). Calculate the pressure built up inside the vessel resulting from the increased temperature, in units of inches water column ("W.C.).

file i02970

Question 32

An absolute pressure gauge is connected to a hollow metal sphere containing a gas:



According to the Ideal Gas Law, the relationship between the gauge's pressure indication and the sphere's temperature is as follows:

$$PV = nRT$$

Unfortunately, though, we do not happen to know the volume of the sphere (V) or the number of moles of gas contained within (n). At best, all we can do is express the relationship between P and T as a proportionality, or as an equality with a *constant of proportionality* (k) accounting for all the unknown variables and unit conversions:

$$P \propto T \qquad\qquad P = kT$$

Calculate the value of this constant (k) if you happen to know that the pressure gauge registers 1.5 bar (absolute) at a temperature of 280 K. Then, predict the temperature when the pressure gauge reads 1.96 bar (absolute).

file i02992

Question 33

A very useful principle in physics is the *Ideal Gas Law*, so called because it relates pressure, volume, molecular quantity, and temperature of an ideal gas together in one neat mathematical expression:

$$PV = nRT$$

Where,

P = Absolute pressure (atmospheres)
V = Volume (liters)
n = Gas quantity (moles)
R = Universal gas constant (0.0821 L · atm / mol · K)
T = Absolute temperature (K)

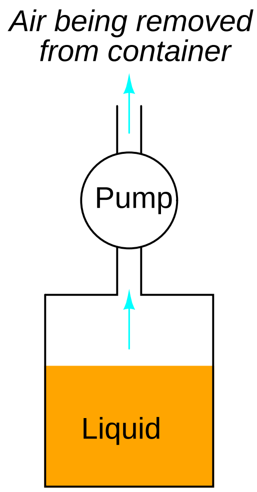
Note that temperature T in this equation must be in *absolute* units (Kelvin). Modify the Ideal Gas Law equation to accept a value for T in units of ^{o}C.

Then, modify the equation once more to accept a value for T in units of ^{o}F.

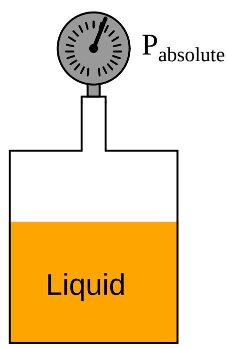
file i00342

Question 34

Suppose that a liquid is placed into a container, and then all the air is drawn out of that container using a vacuum pump:

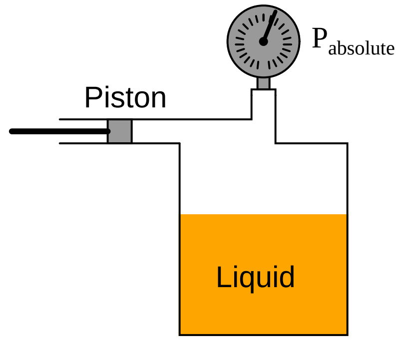


The container is then sealed, and the absolute pressure measured with some kind of pressure instrument:



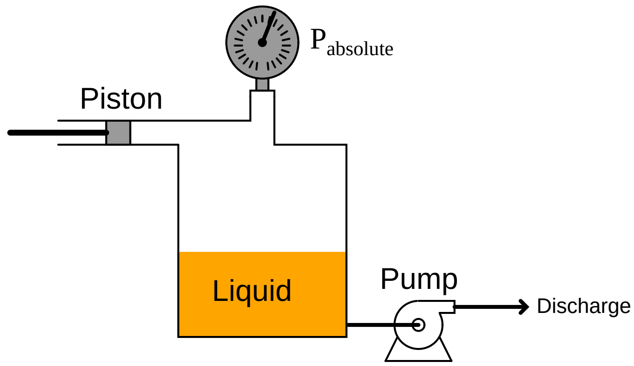
As the liquid is trapped inside the container, thermal energy liberates some of the molecules into the vacuum above, resulting in a vapor forming above the liquid. As some of these vapor molecules strike the walls of the container, they condense back into liquid and dribble down into the liquid pool below. When the rates of evaporation and condensation reach equilibrium, we say the liquid/vapor process is in a condition of *saturation*, and the amount of pressure inside this vessel as the *saturated vapor pressure* of the substance. "Saturated" simply refers to the condition where the rates of evaporation and condensation exactly match; when the space above the liquid can hold no more vapor molecules.

Suppose we now attach a piston to this container so we may change the volume of the vapor space:



If the system reaches a state of saturation (evaporation and condensation rates equal), and temperature remains the same, what will happen to the pressure in the container if the piston is moved inward, thus decreasing volume? Does the pressure increase, decrease, or stay the same?

Now suppose we attach a pump to the bottom of this container so we may remove some of the liquid without letting any air in:

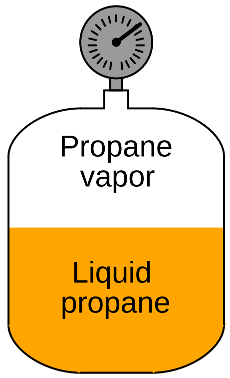


If the system reaches a state of saturation (evaporation and condensation rates equal), and temperature remains the same, what will happen to the pressure in the container as liquid is drawn out? Does the pressure increase, decrease, or stay the same?

file i00348

Question 35

A propane tank holds both liquid propane and propane vapor at high pressure:



How may the pressure in the tank be altered? What physical variable must be changed in order to increase or decrease the vapor pressure inside the tank?

file i00349

Answer 1

Answer 2

The falling weight pulls the string and turns the paddles inside the water-filled container, thereby causing the temperature of the water to rise. Relevant data include:

- Initial temperature of the water
- Final temperature of the water
- *Calculated water temperature rise* $\Delta T = T_f - T_o$

- Mass of water
- Specific heat of water
- Mass of paddle assembly
- Specific heat of paddle assembly
- Mass of thermometer
- Specific heat of thermometer

- Magnitude of the weight
- Initial height of the weight
- Final height of the weight
- *Calculated displacement* $\Delta x = x_f - x_o$

Relevant equations:

$$W = F\Delta x \qquad Q = mc\Delta T$$

Answer 3

If the caloric theory of heat were correct, then the cannon barrel would not be heated by a dull tool, but only heated when bored out with a sharp tool. If heat is a fluid released by cutting, then only successful cutting of the metal (not unsuccessful grinding of a dull tool against the cannon barrel) would cause the water to heat up. A dull tool should, according to the caloric theory, *liberate less heat than a sharp tool.* What Thompson found instead was that a dull tool actually liberated more heat than a sharp tool because it allowed the fruitless grinding process to continue long after it would have taken a sharp tool to bore the hole. In summary, Thompson's experiment demonstrated that heat was a function of mechanical work, not of cleaving metal.

Answer 4

Sensible heat is any form of heat transfer resulting in a temperature change. The relationship between heat transferred (Q) and temperature change (ΔT) is proportional to both the mass of the sample and its *specific heat capacity* (c):

$$Q = mc\Delta T$$

Latent heat is any form of heat transfer resulting in a phase change (e.g. solid to liquid, liquid to gas, or vice-versa). The relationship between heat transferred (Q) and the amount of mass undergoing a phase change (m) it the *latent heat capacity* of the sample (L):

$$Q = mL$$

Answer 5

Some practical examples (by no means an exhaustive list) are given here:

- *Conductive* transfer resulting in *sensible* heat: *Placing a frying pan on a hot stove causes the pan's temperature to rise.*
- *Convective* transfer resulting in *sensible* heat: *Pointing the flame of a propane torch on to a metal surface causes that metal's temperature to rise.*
- *Radiant* transfer resulting in *sensible* heat: *Feeling the increased skin temperature resulting from standing several yards away from a large bonfire.*
- *Conductive* transfer resulting in *latent* heat: *An ice cube placed on a warm frying pan will melt into water.*
- *Convective* transfer resulting in *latent* heat: *A hair dryer causes liquid water in your hair to be forced into a vapor state.*
- *Radiant* transfer resulting in *latent* heat: *A frozen ice puddle melting under the sun's rays.*

Sensible heat (resulting in a temperature change):

$$Q = mc\Delta T$$

Where,
Q = Heat gain or loss (metric calories or British BTU)
m = Mass of sample (metric grams or British pounds)
c = Specific heat of substance
ΔT = Temperature change (metric degrees Celsius or British degrees Fahrenheit)

Latent heat (resulting in a phase change):

$$Q = mL$$

Where,
Q = Heat of transition required to completely change the phase of a sample (metric calories or British BTU)
m = Mass of sample (metric grams or British pounds)
L = Latent heat of substance

Answer 6

The copper block will cool at a faster rate, because copper has less specific heat than iron, meaning that any given amount of heat energy lost will decrease its temperature more than it will iron for the same amount of heat energy loss. Another way of saying this is that the copper contains less heat energy than the iron, even though they both start out at the same temperature.

$c_{Cu} = 0.093$ cal/g$\cdot^o$C

$c_{Fe} = 0.113$ cal/g$\cdot^o$C

Answer 7

This is a problem of specific heat, following this formula:

$$Q = mc\Delta T$$

In order to calculate the amount of heat energy (Q) needed for the task, we need to know the mass of the hot tub's water (m), the specific heat of water (1 BTU per pound per degree F), and the temperature rise (ΔT = 102 ^{o}F − 58^{o}F = 44 ^{o}F). We were given the volume of water (70 gallons), but not its mass in pounds, so we need to do a units conversion based on water having a density of 62.4 pounds per cubic foot:

$$\left(\frac{70 \hbox{ gal}}{1}\right)\left(\frac{231 \hbox{ in}^3}{1 \hbox{ gal}}\right)\left(\frac{1 \hbox{ ft}^3}{1728 \hbox{ in}^3}\right)\left(\frac{62.4 \hbox{ lb}}{\hbox{ft}^3}\right) = 583.9 \hbox{ lb}$$

Now, we are all set to calculate the required heat energy:

$$Q = mc\Delta T$$

$$Q = (583.9 \hbox{ lb})(1 \hbox{ BTU/lb-}^o\hbox{F})(102^o\hbox{F} - 58^o\hbox{F})$$

$$Q = 25692.3 \hbox{ BTU}$$

Answer 8

What we're trying to solve for here is the water mass necessary to deliver 19000 calories of sensible heat to Jane's ear, given a known drop in temperature. Clearly, then, we need to apply the specific heat formula, solving for m:

$$Q = mc\Delta T$$

$$m = \frac{Q}{c\Delta T}$$

$$m = \frac{19000 \hbox{ cal}}{(1 \hbox{ cal/g-}^o\hbox{C})(54^o\hbox{C} - 31^o\hbox{C})}$$

$$m = 826.1 \hbox{ grams}$$

Conveniently, 1 liter of water happens to be 1000 grams. So, what we need is 0.8261 liters of water in Jane's water bottle.

This will be a *low* estimate, as not all of the heat liberated by the cooling water will transfer into Jane's irritated ear canals. Some heat will transfer into other parts of her head, and a fair amount of heat will be lost to the ambient air. Thus, Jane will actually need *more* than 0.8261 liters of hot water to do the job.

Answer 9

This is a calorimetry problem, where we must use the specific heat of water (1 BTU per pound-degree F) to calculate the necessary heat for raising its temperature a specified amount (from 51 ^{o}F to 205 ^{o}F):

$$Q = mc\Delta T$$

Before we may use this formula, however, we need to figure out the mass (in pounds) for 5 gallons of water:

$$\left(\frac{5 \hbox{ gal}}{1}\right) \left(\frac{231 \hbox{ in}^3}{1 \hbox{ gal}}\right) \left(\frac{1 \hbox{ ft}^3}{1728 \hbox{ in}^3}\right) \left(\frac{62.4 \hbox{ lb}}{\hbox{ft}^3}\right) = 41.71 \hbox{ lb}$$

Now we are ready to plug all the values into our specific heat formula:

$$Q = mc\Delta T$$

$$Q = (41.71 \hbox{ lb})(1 \hbox{ BTU/lb} \cdot ^o \hbox{ F})(205^o\hbox{F} - 51^o\hbox{F}) = 6423 \hbox{ BTU}$$

If dry wood has a fuel value of 9000 BTU per pound, Sally should only (theoretically) need 0.713 pounds (11.4 ounces) of dry wood for this fire.

However . . . we know that not all the heat from an open campfire gets tranferred to the water kettle. Given the many forms of heat loss (radiation away from the kettle, convection up into the open air, evaporation of the heating water, etc., etc.), we can count on only a small fraction of the wood fire's heat going into useful heating of the 5 gallons of water. Therefore, Sally will probably need to gather at least several pounds of wood to do the job.

Answer 10

Sensible heat lost by the iron (c_{Fe} = 0.113 cal/g$\cdot^o$C) as it cools to the final temperature will be equal to the sensible heat gained by the copper (c_{Cu} = 0.093 cal/g$\cdot^o$C) as it warms to the final temperature:

$$Q_{iron-lost} = Q_{copper-gained}$$

$$m_{Fe}c_{Fe}(150 - T) = m_{Cu}c_{Cu}(T - 20)$$

$$(15)(0.113)(150 - T) = (25)(0.093)(T - 20)$$

$$(1.695)(150 - T) = (2.325)(T - 20)$$

$$254.25 - 1.695T = 2.325T - 46.5$$

$$300.75 = 4.02T$$

$$T = \frac{300.75}{4.02}$$

$$T = 74.81^o\hbox{C}$$

Answer 11

Sensible heat lost by the water as it cools to the final temperature will be equal to the sensible heat gained by both the steel vessel and the wheat flour:

$$Q_{water-lost} = Q_{wheat-gained} + Q_{steel-gained}$$

$$m_{water}c_{water}(120 - T) = m_{wheat}c_{wheat}(T - 60) + m_{steel}c_{steel}(T - 60)$$

$$(180)(1)(120 - T) = (75)(0.43)(T - 60) + (22)(0.12)(T - 60)$$

$$(180)(120 - T) = (32.25)(T - 60) + (2.64)(T - 60)$$

$$(180)(120 - T) = (32.25 + 2.64)(T - 60)$$

$$(180)(120 - T) = (34.89)(T - 60)$$

$$\frac{(180)(120 - T)}{34.89} = T - 60$$

$$\frac{21600 - 180T}{34.89} = T - 60$$

$$619.09 - 5.16T = T - 60$$

$$679.09 = 6.16T$$

$$T = \frac{679.09}{6.16} = 110.26^o\text{F}$$

Answer 12

In order of most heat required to least heat required:

- To boil a pound of water completely into steam (warming it from 211^o F to 213^o F).
- To melt a pound of ice completely into water (warming it from 31^o F to 33^o F).
- To heat a pound of water from 60^o F to 65^o F.

Answer 13

To raise the water's temperature from 20^o C to 100^o C will require this much heat energy:

$$Q = mc\Delta T$$

$Q = (5 \text{ g})(1 \text{ cal/g-C}^o)(100^o \text{ C} - 20^o \text{ C})$

$Q = (5 \text{ g})(1 \text{ cal/g-C}^o)(80^o \text{ C})$

$Q = 400 \text{ cal}$

This leaves 600 calories remaining from the original 1000 calorie heat dose to boil water into steam. Since the latent heat of vaporization is 540 calories/gram, 600 calories will vaporize this many grams of water:

$$L_v = \frac{Q}{m}$$

$$m = \frac{Q}{L_v}$$

$m = (600 \text{ cal})/(540 \text{ cal/g})$

$m = 1.111 \text{ g}$

Thus, 1.111 grams of water will boil into steam, and then the 1000 calories of heat energy will be spent.

Answer 14

Calculation in three steps:

Heat lost as steam cools from 400 ^{o}F to 212 ^{o}F:

$$Q = mc\Delta T = (2 \text{ lb})(0.476 \text{ BTU/lb} \cdot^o \text{F})(400^o\text{F} - 212^o\text{F}) = 178.98 \text{ BTU}$$

Heat lost as steam condenses to water:

$$Q = mL = (2 \text{ lb})(970.3 \text{ BTU/lb}) = 1940.6 \text{ BTU}$$

Heat lost as water cools from 212 ^{o}F to 125 ^{o}F:

$$Q = mc\Delta T = (2 \text{ lb})(1 \text{ BTU/lb} \cdot^o \text{F})(212^o\text{F} - 125^o\text{F}) = 174 \text{ BTU}$$

Total Heat Lost = 178.98 + 1940.6 + 174 = **2293.58 BTU**

Calculation using enthalpy values (from a steam table):

Enthalpy of 400 ^{o}F superheated steam at 1 atm = 1239.9 BTU/lb = 2479.8 BTU for two pounds steam

Enthalpy of two pounds 125 ^{o}F water (heat lost cooling down to 32 ^{o}F):

$$Q = mc\Delta T = (2)(1)(125 - 32) = 186 \text{ BTU}$$

Total Heat Lost = 2479.8 − 186 = **2293.8 BTU**

Answer 15

The *saturated vapor pressure* of a substance is a direct function of temperature. If we increase the heat rate so as to boil water faster, we will build up more pressure in the vessel, causing the boiling point to rise. Continued heat flow into the water from the burner will then cause the temperature to rise to match the rising boiling point.

If we try to vent more steam, we cause the pressure in the vessel to decrease. More water begins to boil, which removes heat energy from the water, causing its temperature to drop.

A sophisticated way of stating the problem is that the student assumed *two degrees of freedom* in this process, where there in fact is only one degree of freedom.

Answer 16

Partial answer:

- T = 501 ^{o}F and P = 810 PSIG :
- T = 250 ^{o}F and P = 75 PSIG : **water only**
- T = 690 ^{o}F and P = 1886 PSIG : **steam only**, approximately **61 deg F** superheat
- T = 369 ^{o}F and P = 550 PSIG :
- T = 274 ^{o}F and P = 30 PSIG : **water and steam mixed**
- T = 471 ^{o}F and P = 405 PSIG :

Answer 17

Since the latent heat of vaporization for water is 970 BTU/lb_m, and we wish to boil 300 pounds of steam per hour, this equates to the following number of BTUs each and every hour:

$$Q = mL_v$$

$Q = (300 \text{ lb}_m)(970 \text{ BTU/lb}_m)$

$Q = 291{,}000$ BTU

Thus, the required heat input to the boiler (assuming 100% efficiency) is 291,000 BTU/hour. Since no boiler is perfectly efficient, though, the actual required heat input will be greater than this.

Answer 18

The temperature of saturated steam is a direct function of its pressure. 232 PSIG is 246.7 PSIA (at sea level), and looking up this pressure in a saturated steam table (I'm using *Thermal Properties of Saturated and Superheated Steam* by Lionel Marks and Harvey Davis, published in 1920), the nearest pressure I see is 247.1 PSIA, which corresponds to **400 ^{o}F**.

At that pressure and temperature the enthalpy (total heat, h) given by this steam table is 1201.3 BTU per pound, which is the amount of heat necessary to raise the temperature of one pound of water from 32 ^{o}F to this boiler's temperature of 400 ^{o}F. This isn't our final answer for required heat, though, because our feedwater is starting at 63 ^{o}F rather than from 32 ^{o}F which is the reference temperature assumed by steam tables when specifying enthalpy. The amount of heat absorbed by each pound of water passing through this boiler is the *difference* between the steam's enthalpy and the feedwater's enthalpy.

The feedwater's enthalpy is simply calculated by subtracting 32 from its temperature, because the specific heat of water at low temperatures is 1 (i.e. 1 BTU required to change the temperature of 1 pound of water by 1 degree Fahrenheit). Thus, the feedwater's enthalpy is $63 - 32 = 31$ BTU per pound. Therefore, the amount of heat gained by feedwater passing through this boiler is 1201.3 BTU/lb $-$ 31 BTU/lb = **1170.3 BTU/lb**.

If the amount of heat absorbed by every pound of feedwater is 1170.3 BTU, and there are 20 pounds flowing through the boiler every minute, the heat rate may be calculated by multiplication:

$$\left(\frac{1170.3 \text{ BTU}}{\text{lb}}\right)\left(\frac{20 \text{ lb}}{\text{min}}\right) = \mathbf{23406\ BTU/min}$$

Answer 19

First, let's calculate the heat demand of the maple syrup. Raising just one pound of this syrup from 57 ^{o}F to 210 ^{o}F requires the following amount of heat:

$$Q = mc\Delta T$$

$$Q = (1 \text{ lb})(0.95 \text{ BTU/lb-degF})(210 - 57 \text{ deg F}) = 145.35 \text{ BTU}$$

With a mass flow rate of 12 pounds per minute, the syrup will require this much heat rate from the steam:

$$\frac{dQ}{dt} = \left(\frac{145.35 \text{ BTU}}{\text{lb}}\right)\left(\frac{12 \text{ lb}}{\text{min}}\right) = 1744.2 \text{ BTU/min}$$

Consulting a steam table, we find that the enthalpy of 300 ^{o}F saturated steam is 1179.1 BTU per pound. Since we know the steam doesn't cool all the way down to 32 ^{o}F upon leaving the exchanger, but only cools down to 130 ^{o}F water, we must subtract the enthalpy of that water to determine the amount of heat delivered by each pound of steam passing through the exchanger:

$$1179.1 - (130 - 32) = 1081.1 \text{ BTU/lb}$$

Computing necessary steam flow is a simple matter of division:

$$\frac{1744.2 \text{ BTU/min}}{1081.1 \text{ BTU/lb}} = 1.6134 \text{ lb/min}$$

It may be easier to see the unit cancellation if we express this in terms of multiplication rather than division:

$$\left(\frac{1744.2 \text{ BTU}}{\text{min}}\right)\left(\frac{\text{lb}}{1081.1 \text{ BTU}}\right) = 1.6134 \text{ lb/min}$$

Answer 20

Calculating the mass of water leaving the tower is simple: the Law of Mass Conservation states that mass cannot be created or destroyed, and so all of the 1000 pounds must be accounted for. If 50 pounds left in the form of vapor, then the remaining liquid must have a mass equal to the difference between the incoming water and the exiting vapor:

$$m_{water-out} = m_{water-in} - m_{vapor}$$

$$m_{water-out} = 1000 \text{ lb} - 50 \text{ lb}$$

$$m_{water-out} = 950 \text{ lb}$$

The Law of Energy Conservation similarly states that all energy must be accounted for as well. The incoming water has an enthalpy of 105 BTU per pound (137 ^{o}F − 32 ^{o}F times one BTU per pound per degree F), which for 1000 pounds equals 105,000 BTU. This 105,000 BTU must be exactly equal to the heat content of the 50 pounds vapor plus the heat content of the 950 pounds water leaving the tower.

To determine the enthalpy of the vapor (at 111 ^{o}F and atmospheric pressure), we shall consult a steam table. The enthalpy of steam at 111 ^{o}F is 1108.4 BTU per pound per degree F, which for 50 pounds of vapor equals 55,420 BTU of heat energy carried away from the tower by the vapor. Subtracting this heat energy value from the total heat coming into the tower (105,000 BTU) leaves us with 49,580 BTU heat content for the liquid water exiting the tower. With the mass of this water being 950 pounds, it means its enthalpy must be $\frac{Q}{m}$ = 52.19 BTU per pound. This puts the exiting water's temperature at 52.19 degrees above freezing (32 ^{o}F), or 84.19 ^{o}F.

Answer 21

- What advantages might there be with this design versus a furnace installed inside the home? *Safety (no fire hazard or smoke hazard inside the home), Efficiency (wood fires are very efficient and practically smokeless when burned at full intensity as is permitted with a heat-storage system like this), Convenience (the fire need not be tended for hours each day, but rather is lit and forgotten until the next fire needs to be lit)*
- Why is *sand* a good choice as a heat-storage medium inside the furnace structure? *Sand does not melt, freeze, corrode, or leak. It has a high density and a reasonable heat capacity (approximately 0.19).*
- Is the heat storage in this system based on *specific heat* or *latent heat*? *Since the sand does not change phase with the temperature of the furnace, this system is based on specific heat.*
- Is the heat transfer in this system (from heater to home) based on *specific heat* or *latent heat*? *Since the water does not boil in the heater, the transfer is strictly a function of specific heat. If the water was boiled into steam and then sent to the house, the energy transfer would involve latent heat as well as specific heat!*
- How may the home's temperature be thermostatically controlled? *A pump circulating the water between the furnace and the house may be cycled by a thermostat control.*
- How to equip the system with an alarm prompting the user to light a new fire in the furnace? *A low-temperature alarm with a sensor embedded in the sand reservoir would suffice.*
- Calculate the enthalpy of the water as it enters the home (from the heater) at a temperature of 184 ^{o}F. *Enthalpy is simply the amount of heat energy released per pound of mass based on the temperature falling down to 32 ^{o}F (0 ^{o}C).* $Q = mc\Delta T$ *= (1 lb)(1 BTU/lb-degF)(184 deg F − 32 deg F) = 152 BTU. Therefore, the enthalpy of the water entering the home is 152 BTU/lb.*
- Calculate the enthalpy of the water as it leaves the home (on its way to the heater) at a temperature of 127 ^{o}F. *Enthalpy is simply the amount of heat energy released per pound of mass based on the temperature falling down to 32 ^{o}F (0 ^{o}C).* $Q = mc\Delta T$ *= (1 lb)(1 BTU/lb-degF)(127 deg F − 32 deg F) = 95 BTU. Therefore, the enthalpy of the water exiting the home is 95 BTU/lb.*
- Calculate the rate of heat delivered to the home by this hot water assuming a water mass flow rate of 9.2 pounds per minute. *For every pound of heating water that circulates through the home, the amount of energy it delivers to the home is simply the difference between the incoming and outgoing enthalpy values. 152 BTU/lb − 95 BTU/lb = 57 BTU/lb. At a water flow rate of 9.2 pounds per minute, this equates to a heating rate of 524.4 BTU per minute, or 31,464 BTU per hour.*

Answer 22

The saturation temperature of steam at 505 PSIG (greater than 495 PSIG) is 471 ^{o}F. Since 780 ^{o}F is much greater than this, we may deduce that the steam in the hot leg is superheated, and thus the core must be adding heat to the steam after it has boiled away from the water. Thus, the core is uncovered.

This is a very bad situation!!

Answer 23

We may calculate the heat rate input to this turbine by subtracting enthalpy values ($h_{in} - h_{out}$) and multiplying by the mass flow rate of the steam:

Input enthalpy (from steam table; 583 ^{o}F and 88 PSIG) = 1314.4 BTU/lb

Output enthalpy (from steam table; 91 ^{o}F and −14 PSIG) = 1099.6 BTU/lb

Difference in enthalpy values from inlet to discharge of turbine = 1314.4 BTU/lb − 1099.6 BTU/lb = 214.8 BTU/lb

Heat rate = (214.8 BTU/lb)(2300 lb/min) = 494,040 BTU/min = 29,642,400 BTU/h

We may convert this heat rate (power) into watts by using the conversion equivalence of 745.7 watts and 2544.43 BTU/h:

(29642400 BTU/h) (745.7 W / 2544.43 BTU/h) = 8,687,343.6 W = 8.69 MW

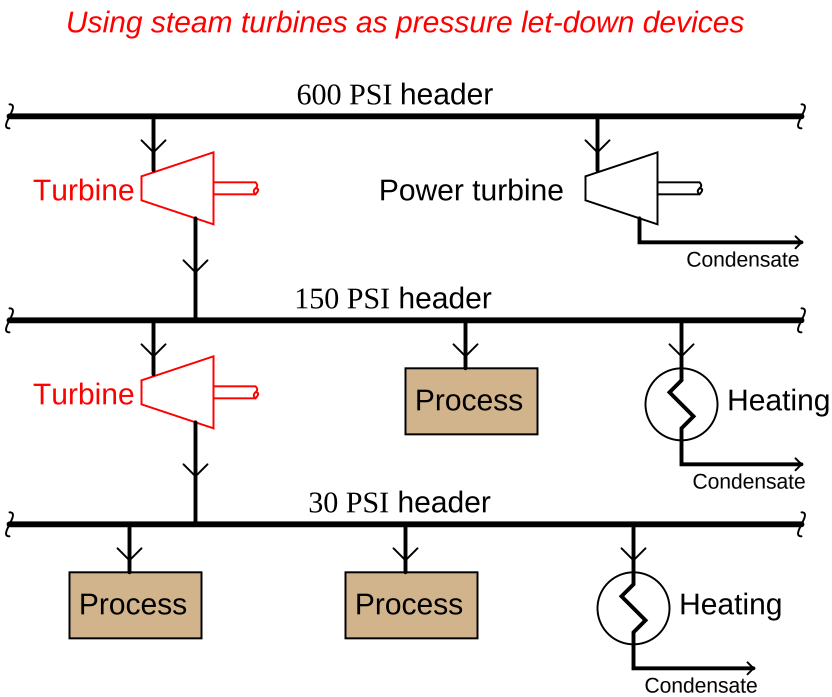
Since the turbine is 80% efficient, only 80% of this heat rate gets converted into mechanical shaft power. Therefore,

(8.69 MW)(0.80) = **6.95 MW** shaft power

Answer 24

The water injected in a desuperheating valve gains heat energy from the superheated let-down steam, producing a greater volume of steam at a lower pressure (and lower temperature), much like an electrical transformer steps down voltage with a corresponding *increase* in current. Desuperheaters exchange temperature for volume, much like transformers exchange voltage for current (or vice-versa).

Challenge question: explain why turbines make efficient steam pressure let-down devices:



Answer 25

First, we need to determine the areas of the trailer surfaces, along with their respective R-values for insulation, to calculate total heat rate demand to maintain the interior temperature:

Total area of side walls = $(28 \text{ ft}^2)(8 \text{ ft}^2)(2) = 448 \text{ ft}^2$

Total area of end walls = $(12 \text{ ft}^2)(8 \text{ ft}^2)(2) = 192 \text{ ft}^2$

Wall heat loss rate = $\frac{A\Delta T}{R} = \frac{(448+192)(75-20)}{5} = 7040$ BTU/hour

Area of floor = $(28 \text{ ft}^2)(12 \text{ ft}^2) = 336 \text{ ft}^2$

Floor heat loss rate = $\frac{A\Delta T}{R} = \frac{(336)(75-20)}{7} = 2640$ BTU/hour

Area of ceiling = $(28 \text{ ft}^2)(12 \text{ ft}^2) = 336 \text{ ft}^2$

Ceiling heat loss rate = $\frac{A\Delta T}{R} = \frac{(336)(75-20)}{10} = 1848$ BTU/hour

TOTAL heat loss rate = 7040 BTU/hour + 2640 BTU/hour + 1848 BTU/hour = **11528 BTU/hour**

Consulting a saturated steam table (I'm using *Thermal Properties of Saturated and Superheated Steam* by Lionel Marks and Harvey Davis, published in 1920), we find that 34.5 PSIG steam (49.2 PSIA) is very nearly 280 ^{o}F, and has an enthalpy (total heat) value of 1173.3 BTU per pound. The enthalpy of the hot water leaving the radiator is simply the difference between its temperature and 32 ^{o}F: 110 − 32 = 78 BTU per pound. Therefore, every pound of steam passing through the radiator will release heat equal to the difference between the entering and exiting enthalpy values: 1173.3 BTU/lb − 78 BTU/lb = 1095.3 BTU/lb.

Dividing the necessary heat rate (in BTU/hour) by the released heat of each pound of steam (in BTU/lb) will yield a steam flow rate in lb/hour:

$$\frac{11528 \text{ BTU/hour}}{1095.3 \text{ BTU/lb}} = \textbf{10.525 lb/hour}$$

Answer 26

Heat loss equation given temperature difference, surface area, and R value:

$$\frac{dQ}{dt} = \frac{A\Delta T}{R}$$

A good problem-solving approach is to neatly organize the given values and calculate surface areas before plugging these values into the heat transfer equations:

- Tank roof = 101 square feet with R-value of 4
- Tank floor = πr^2 = 78.54 square feet with R-value of 2
- Tank walls = $2\pi rh$ = 408.4 square feet with R-value of 5 per inch (1.5 inches thick)

Heat loss through the roof:

$$\frac{dQ}{dt} = \frac{A\Delta T}{R} = \frac{(101)(95-40)}{4} = 1388.75 \text{ BTU/hr}$$

Heat loss through the floor:

$$\frac{dQ}{dt} = \frac{A\Delta T}{R} = \frac{(78.54)(95-40)}{2} = 2159.84 \text{ BTU/hr}$$

Heat loss through the walls:

$$\frac{dQ}{dt} = \frac{A\Delta T}{R} = \frac{(408.4)(95-40)}{(5)(1.5)} = 2995.0 \text{ BTU/hr}$$

Total heat loss rate = 6543.6 BTU/hour

Total fuel demand rate = 7883.8 BTU/hour (at 83% boiler efficiency)

Answer 27

In the heat exchanger where the two fluids move in the same direction, the heated fluid can never exit the exchanger at a warmer temperature than the heating fluid exits. With the contra-flow design, it can!

Answer 28

$\frac{dQ}{dt}$ = Rate of heat flow (Watts)
e = Emissivity factor (*unitless*)
A = Area of radiating surface (square meters)
T = Absolute temperature (Kelvin)

Challenge question: a more complete expression of the Stefan-Boltzmann equation takes into account the temperature of the warm object's surroundings:

$$\frac{dQ}{dt} = e\sigma A(T_1^4 - T_2^4)$$

Where,
T_1 = Temperature of the object
T_2 = Ambient temperature

Explain why this second T term is necessary for the equation to make sense.

Answer 29

$$V \approx V_0(1 + 3\alpha \Delta T)$$

Answer 30

$P = 1.422$ atmospheres = 42.8 kPaG

Answer 31

Assuming volume (V), molecular gas quantity (n), and the Gas Constant (R) never change, the Ideal Gas Law may be reduced as follows:

$$P_1 V = nRT_1$$

$$P_2 V = nRT_2$$

$$\frac{P_1 V}{P_2 V} = \frac{nRT_1}{nRT_2}$$

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

$$P_2 = P_1 \frac{T_2}{T_1}$$

P_1 at 0^o C = 1 atm = 14.7 PSIA
T_1 at 0^o C = 273.15 K
T_2 at 70^o F = 21.11^o C = 294.26 K

$$P_2 = 14.7 \text{ PSIA} \left(\frac{294.26 \text{ K}}{273.15 \text{ K}} \right)$$

$P_2 = 15.84$ PSIA = 1.136 PSIG = 31.5 "W.C.

Answer 32

$k = 0.00536$

$T = 365.9$ K at $P = 1.96$ bar

Answer 33

$$PV = nR(T + 273.15) \qquad \text{Temperature in degrees C}$$

$$PV = nR\left(\frac{5}{9}(T - 32) + 273.15\right) \qquad \text{Temperature in degrees F}$$

It should be noted that the behavior of real gases departs significantly from the Ideal Gas Law model at temperatures near absolute zero, especially when phase changes (liquefaction and/or solidification) take place. Still, it is possible through intuition to tell the intended unit of temperature measurement for T in this equation must be absolute and not elevated, and this is the thrust of the challenge question.

Answer 34

In both cases (piston moving in, and pump pulling liquid out) there will be an initial change in pressure. However, the pressure will stabilize at the exact same quantity it was at before once equilibrium is re-established. Saturated vapor pressure does not depend on the quantity of liquid or vapor, or the volume of the enclosed space!

Initially, the pressure will increase because the vapor will be forced into a smaller volume (remember $PV = nRT$). This will cause the rate of condensation (vapor-to-liquid) to increase and the rate of evaporation (liquid-to-vapor) to decrease. As excess vapor re-condenses into liquid, the pressure will decrease due to a lesser molar quantity of vapor (the n in $PV = nRT$) in the space above the liquid. Eventually, the pressure will stabilize at the exact same quantity it was at before, when the system reaches a state of saturation again.

Answer 35

The only factor able to alter the saturated vapor pressure inside the tank is *temperature*. Increasing the tank's temperature will cause the pressure to likewise increase.

This principle is put to use in Class II filled systems for measuring temperature: the vapor pressure of the volatile fill fluid indicates its temperature. Since this pressure does not depend on volume, any changes in volume resulting from expansion or contraction of the liquid or the vapor at the indicator end of the system will be absorbed by either condensation or evaporation (respectively), until the pressure again stabilizes at the value determined by the liquid/vapor interface's temperature.