Energy Balances without Reaction

1. Introduction to Energy Balance for Processes Without Reaction

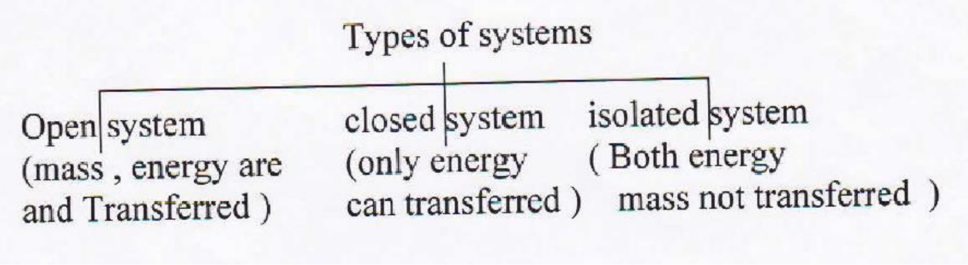
In the last lecture, we discussed Q, W, U, and H but did not try to relate them in an energy balance. In this lecture we explain what energy balances are all about. We also show you how to formulate, simplify, and solve energy balances for variables of interest. This lecture focuses on processes without chemical reaction. As you know, the principle of the conservation of energy states that the total energy of a system plus the surroundings can neither be created nor destroyed.

1.1 General Energy Balance Equation

$$\begin{Bmatrix}\text{Accumulation of}\\ \underline{\textit{energy}}\text{ within}\\ \text{the system}\\ \text{from } t_1 \text{ to } t_2\end{Bmatrix} = \begin{Bmatrix}\text{Final } \underline{\textit{energy}}\\ \text{in the system}\\ \text{at } t_2\end{Bmatrix} - \begin{Bmatrix}\text{Initial } \underline{\textit{energy}}\\ \text{in the system}\\ \text{at } t_1\end{Bmatrix}$$

$$= \begin{Bmatrix}\text{Total cumulative}\\ \underline{\textit{energy}}\text{ flow into}\\ \text{the system from}\\ t_1 \text{ to } t_2\end{Bmatrix} - \begin{Bmatrix}\text{Total cumulative}\\ \underline{\textit{energy}}\text{ flow}\\ \text{out of the system}\\ \text{from } t_1 \text{ to } t_2\end{Bmatrix} + \begin{Bmatrix}\text{Generation of}\\ \underline{\textit{energy}}\text{ within}\\ \text{the system}\\ \text{from } t_1 \text{ to } t_2\end{Bmatrix}$$

$$- \begin{Bmatrix}\text{Consumption of}\\ \underline{\textit{energy}}\text{ within}\\ \text{the system}\\ \text{from } t_1 \text{ to } t_2\end{Bmatrix} \qquad \text{(9.}$$



1.1.1 Steady-State, Closed Systems

For a closed, unsteady-state system the energy balances in the symbols that we have previously defined are:

$$\underbrace{\Delta E_{\text{inside}}}_{\text{accumulation}} \equiv \Delta(U + PE + KE)_{\text{inside}} = \underbrace{Q}_{\text{heat transfer}} + \underbrace{W}_{\text{work}}$$

In closed systems, the values of ΔPE and ΔKE in ΔE are usually negligible or zero; hence, often you see ΔU = Q + W used as the energy balance.

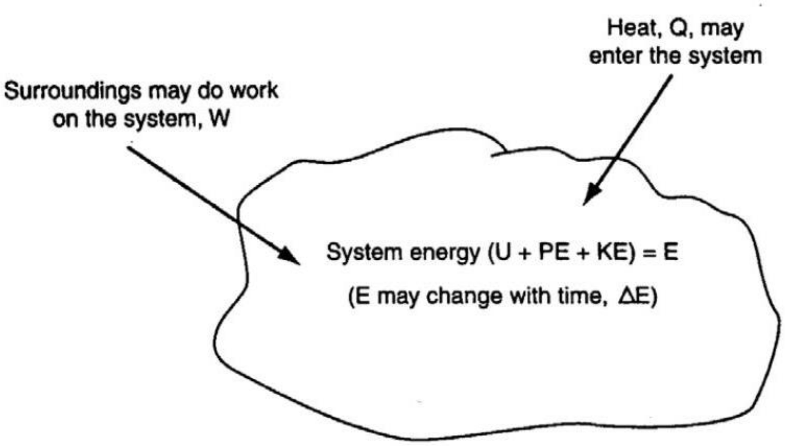
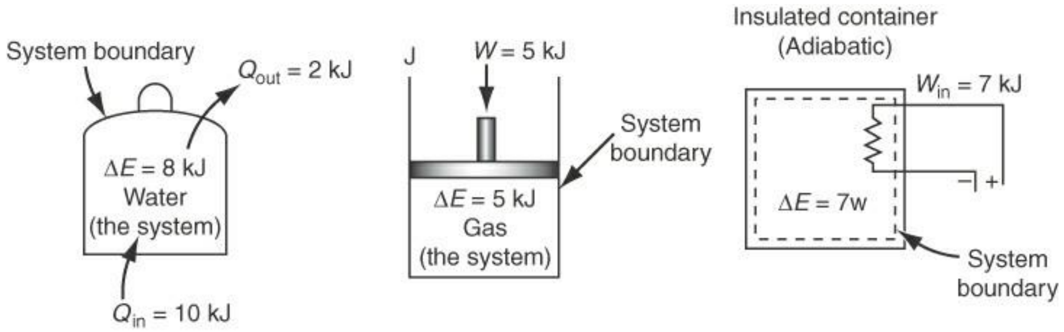


Figure below illustrates three examples of applying above Equation to simple closed, unsteadystate systems.

a) 10 kJ of heat are transferred through the fixed boundary (bottom) of a vessel with 2 kJ being transferred out at the top during the same time period. ΔU increases by 8 kJ.
b) A piston does 5 kJ of work on a gas whose internal energy increases by 5 kJ.
c) The voltage difference between the system and surroundings forces a current into a system in which no heat transfer occurs because of the insulation on the system.



a. Heating water in a closed vessel

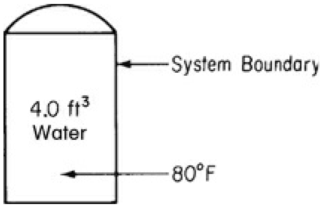
b. Compressing a gas in a cylinder

c. Electrical work done on a resistance heater in an oven

Example 1: Application of the Energy Balance to a Closed System

Ten pounds of water at room temperature (80°F) are stored in a sealed tank that has a volume of 4.0 ft^3. How much heat must be transferred to the tank so that 40% of the water is vaporized? Also, what will be the final temperature and pressure?

Solution



The specific volume of the solution is 4.0/10 = 0.40 ft^3/lb. Neglecting any air with the water in the tank, the initial internal energy is 48.02 Btu/lb.

The material balance is easy: the mass in the system is constant at 10 lb. As to the energy balance,

$$\Delta U = Q + W$$

W is zero because the boundary of the system is fixed, no electrical work is done, and so forth;

$$Q = \Delta U$$

Because the volume of the final state is fixed at 4 ft^3 and the quality of the final state is set at 40%, we can use these conditions to determine the temperature and pressure that satisfy these conditions. We will use the steam table on the CE software on the website that accompanies this text. For 40% quality, there will be 4 lb of saturated steam and 6 lb of liquid. By trial and error, we can select temperatures and calculate the total volume based on the specific volume of the liquid and the specific volume of the vapor. For example, at 400°F, the specific volume of the vapor is 1.863 ft^3/lb and the specific volume of the liquid is 0.019 ft^3/lb. Therefore, the total volume for this case is:

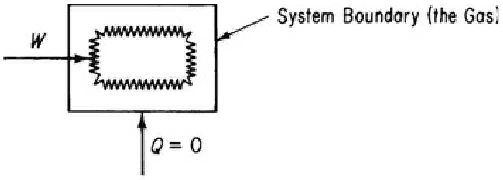
$$V(400°F) = 0.019(6) + 1.863(4) = 7.566\ ft^3$$

Therefore, the assumed temperature was too high. By continuing this trial-and-error procedure, a temperature of 375°F yields a total volume of 4 ft^3. And the corresponding pressure is 184.4 psia. In addition, the internal energy of the vapor and the liquid are provided by the software so that the total internal energy for the final state is 6538.5 Btu. Therefore,

$$Q = \Delta U = 6538.4 - 480.3 = 6058.3 \text{ Btu}$$

Example 2: Application of the Energy Balance to Plasma Etching

Argon gas in an insulated plasma deposition chamber with a volume of 2 L is to be heated by an electric resistance heater. Initially, the gas, which can be treated as an ideal gas, is at 1.5 Pa and 300 K. The 1000-ohm heater draws current at 40 V for 5 min (i.e., 480 J of work is done on the system by the surroundings). What are the final gas temperature and pressure in the chamber? The mass of the heater is 12 g, and its heat capacity is 0.35 J/(g)(K). Assume that the heat transfer through the walls of the chamber from the gas at this low pressure and in the short time period involved is negligible.



Solution

No reaction occurs. The fact that the electric coil is used to “heat” (raise the temperature of) the argon inside the system does not mean that heat transfer takes place to the selected system from the surroundings. Although the net result is an increase in temperature, only work is done, but the electrical work is all converted into thermal energy. The system does not exchange mass with the surroundings; hence it is steady state with regard to mass but is unsteady state with respect to energy.

Because of the assumption about the heat transfer from the chamber wall, $Q = 0$. W is given as +480 J (work done on the system) in 5 min.

Basis: 5 min

$\Delta U = 480$ J. One way to solve the problem is to find the T and p associated with a value of ΔU equal to 480 J. A table, equation, or chart for argon would make this procedure easy. In the absence of such a data source, we fall back on the assumption that the argon gas is an ideal gas (as is true), so that $pV = nRT$. Initially we know p, V, and T and thus can calculate the amount of the gas:

$$n=\frac{pV}{RT}=\frac{1.5\ \text{Pa}}{}\left|\frac{2\ \text{L}}{}\right|\frac{10^{-3}\,\text{m}^3}{1\ \text{L}}\left|\frac{1\ (\text{g mol})\ (\text{K})}{8.314\ (\text{Pa})\ (\text{m}^3)}\right|\frac{}{300\ \text{K}}=1.203\times 10^{-6}\,\text{g mol}$$

You are given the heater mass and its heat capacity of C_v = 0.35 J/(g)(K).

The C_v of the gas can be calculated. Because $C_p=\frac{5}{2}R$ and $C_v-C_p=R$. Thus, $C_v=\frac{3}{2}R$

You have to pick a reference temperature for the calculations. The most convenient reference state is 300 K. Then ΔU for the gas and the heater can be calculated assuming both the heater and the gas end up at the same temperature:

$$\text{Gas:}\quad \Delta U_g=1.203\times10^{-6}\int_{300}^{T}C_v\,dT=1.203\times10^{-6}\left(\frac{3}{2}R\right)(T-300)$$

$$\text{Heater:}\quad \Delta \text{U}_\text{h}=12\,\text{g}\left(\frac{0.35\ \text{J}}{(\text{g})(\text{K})}\right)(T-300)$$

The mass balance is trivial: the mass in the chamber does not change. The unknown is T, and one equation is involved, the energy balance, so the degrees of freedom are zero.

$$\Delta \text{U}=\text{U}_{\text{gas}}+\text{U}_{\text{heater}}$$

$$\Delta U=480\,\text{J}=(12)(0.35)(T-300)+\left(2.302\times10^{-6}\right)\left(\frac{3}{2}\right)(8.314)(T-300)$$

$$T=414\ \text{K}$$

The final pressure is obtained from:

$$\frac{p_2V_2}{p_1V_1}=\frac{n_2\text{R}T_2}{n_1\text{R}T_1}\ \text{or}$$

$$p_2=p_1\left(\frac{T_2}{T_1}\right)=1.5\left(\frac{414}{300}\right)=2.07\ \text{Pa}$$

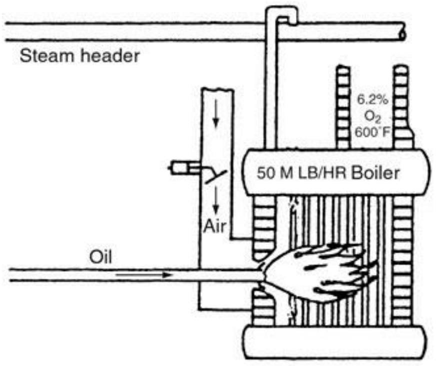
1.1.2 Energy Balances for Open, Steady-State Systems

Figure below shows some examples of open, steady-state processes.

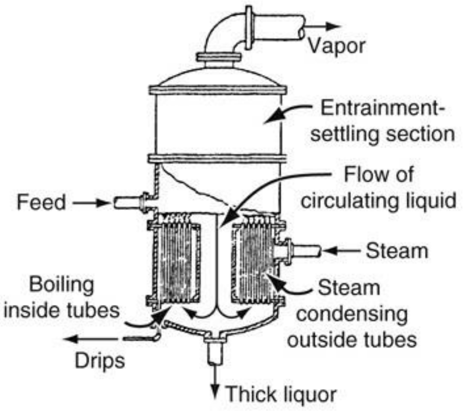
a) A fuel is burned in a boiler to heat tubes through which water flows and becomes steam.

b) A dilute liquid feed containing a solute is concentrated to a "thick liquor." Vapor from the liquid is removed overhead. To provide the necessary heat transfer, steam flows through a steam chest (heat exchanger).

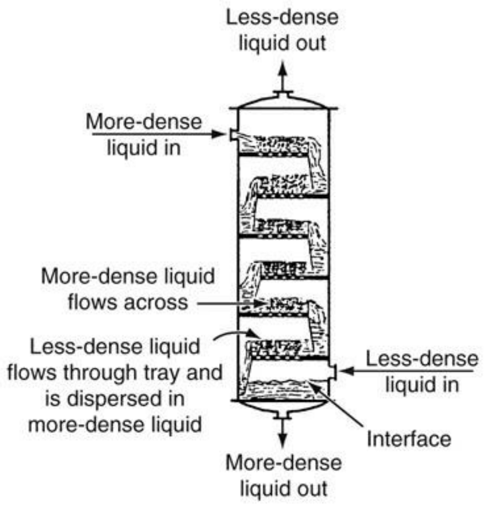
c) a liquid containing a desirable solute is passed through a column countercurrent to an immiscible solvent that favors extracting the solute from the liquid.



a. Boiler to generate steam



b. Evaporator that concentrates a solute



c. Plate extraction column

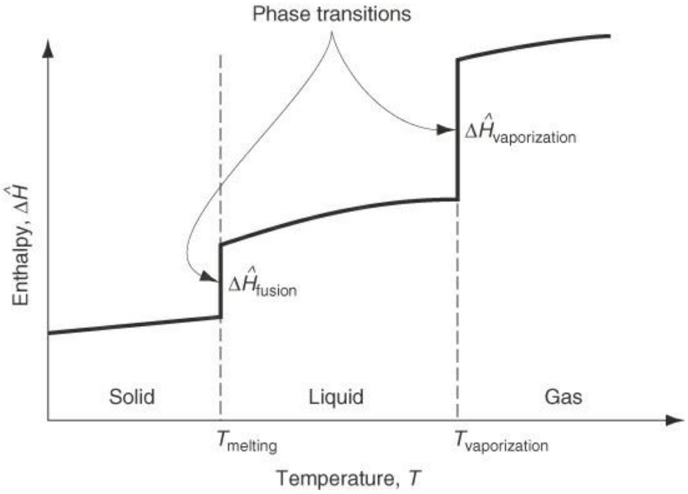
Equation below applies to steady-state, open processes because steady-state means that the final and initial states of the system are the same, $\Delta U_{\text{total}} = 0$. In addition, W, ΔKE, and ΔPE are typically quite small compared to the heat transfer Q. So, the equation become:

$$\Delta H = Q$$

$$H = U + pV$$

Calculating enthalpy with a phase change

Equation of enthalpy: $\Delta\hat{H} = \int_{T_2}^{T_1} C_p dT$ is *not* valid if a phase change occurs. Look at Figure below. The enthalpy associated with a phase change must be included to get the overall ΔH (or $\Delta\hat{H}$).



The **phase transitions** occur from the solid to the liquid phase, and from the liquid to the gas phase, and vice versa. During these transitions, very large changes in the value of the enthalpy (and internal energy) of a substance occur, changes called **latent heat** changes, because they occur without any noticeable change in temperature. Because of the relatively large enthalpy change associated with a phase transition, it is important to get accurate values of any latent heats involved when applying energy balances. For a **single phase**, the enthalpy varies as a function of the temperature. The enthalpy changes that take place within a single phase are usually called **sensible heat** changes.

The enthalpy changes for the common specific phase transitions are termed **heat of fusion** (for melting), ΔH_{fusion}, and **heat of vaporization** (for vaporization), ΔH_v. The word *heat* has been carried by custom from very old experiments in which enthalpy changes were calculated from experimental data that frequently involved heat transfer. *Enthalpy of fusion* and *vaporization* would be the proper terms, but they are not widely used. The **heat of condensation** is the negative of the heat of vaporization, and the **heat of solidification** is the negative of the heat of fusion. The **heat of sublimation** is the enthalpy change associated with the changing of phase from solid directly to vapor.

The overall specific enthalpy change of a pure substance can be formulated by summing the sensible and latent heats (enthalpies) from the initial state to the final state.

Overall enthalpy change Sensible heat of Solid Melting Sensible heat of liquid

$$\Delta\hat{H} = \hat{H}(T) - \hat{H}(T_{\text{ref}}) = \int_{T_{\text{ref}}}^{T_{\text{fusion}}} C_{p,\text{solid}}\, dT + \Delta\hat{H}_{\text{fusion at } T_{\text{fusion}}} + \int_{T_{\text{fusion}}}^{T_{\text{vaporization}}} C_{p,\text{liquid}}\, dT$$

Vaporization Sensible heat of vapor

$$+ \Delta\hat{H}_{\text{vaporization}} \text{ at } T_{\text{vap}} + \int_{T_{\text{ref}}}^{T} C_{p,\text{vapor}}\, dT$$

Example: One hundred grams of H_2O exist in the gas phase at 395 K. How much energy will it take to condense all of the H_2O at 395 K?

Solution: From steam table, $\Delta H_{\text{vap}}(395\text{K}) = 2197$ kJ/kg; energy to condense 100 g = -219.7 kJ.

Tables and Charts to Retrieve Enthalpy Values

The units are kilojoules per kilogram. If you want to calculate the enthalpy change of saturated steam from 305 to 307 K by linear interpolation from a table graduated in 5-degree increments:

$$\hat{H}_{307} = \hat{H}_{305} + \frac{\hat{H}_{310} - \hat{H}_{305}}{T_{310} - T_{305}}(T_{307} - T_{305}) = 2558.9 + \frac{2567.9 - 2558.9}{310 - 305}(307 - 305)$$
$$= 2562.5$$

Enthalpies for Phase Transitions

The enthalpies of phase changes can estimate values for $\Delta\tilde{H}_v$ from one of the relations such as the following three. Use of experimental values for the heat of vaporization is recommended whenever possible.

Chen's equation: An equation that yields values of (in kilojoules per gram mole) [the overlay tilde (~) on *H* designates per mole rather than per mass]

$$\Delta\tilde{H}_v = RT_b\left(\frac{3.978(T_b/T_c)-3.938+1.555\ln p_c}{1.07-(T_b/T_c)}\right)$$

where T_b is the normal boiling point of the liquid in kelvin, T_c is the critical temperature in kelvin, and p_c is the critical pressure in atmospheres.

Riedel's equation:

$$\Delta\tilde{H}_v = 1.093\text{R}\,T_c\left[\frac{T_b(\ln p_c - 1)}{T_c(0.930-(T_b/T_c))}\right]$$

Watson's equation Watson found empirically that below the critical temperature, the ratio of two heats of vaporization could be related by

$$\frac{\Delta\tilde{H}_{v2}}{\Delta\tilde{H}_{v1}} = \left(\frac{1-T_{r2}}{1-T_{r1}}\right)^{0.38}$$

$\Delta\tilde{H}_{v2}$ where of vaporization of a pure liquid at T_1 and $\Delta\tilde{H}_{v1}$ of vaporization of the same liquid at T_2. Yaws4 lists other values of the exponent for various substances.

Q/ Explain why, when a liquid evaporates, the change in enthalpy is greater than the change in internal energy.

Q/ One pound of liquid water is at its boiling point of 575°F. It is then heated at constant pressure to 650°F, then compressed at constant temperature to one-half of its volume (at 650°F), and finally returned to its original state of the boiling point at 575°F. Calculate ΔH and ΔU for the overall process.

Example: Comparison of an Estimate of the Heat of Vaporization with the Experimental Value

Use Chen's equation to estimate the heat of vaporization of acetone at its normal boiling point and compare your results with the experimental value of 30.2 kJ/g mol listed in Appendix E.

The basis is 1 g mol. You have to look up some data for acetone in Appendix E:

Normal boiling point:	328.2 K
***Tc*:**	508.0 K

***pc*:**	47.0 atm

Solution:

The next step is to calculate some of the values of the variables in the estimation equations:

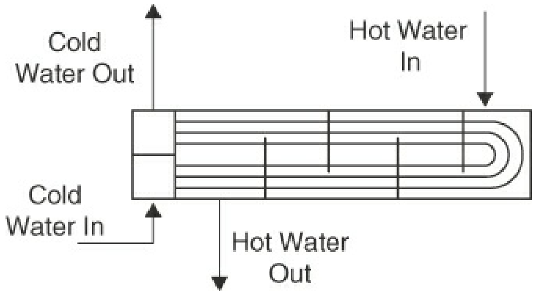
$$\frac{T_b}{T_c} = \frac{329.2}{508.0} = 0.648$$

$$\ln p_c = \ln(47.0) = 3.85$$

$$\Delta\tilde{H}_v = \frac{8.314\times10^{-3}\ \text{kJ}}{(\text{g mol})(K)}\bigg|\ 329.2\ \text{K}\ \bigg|\ \frac{[(3.978)(0.648) - 3.938 + (1.555)(3.85)]}{1.07 - 0.648}$$
$$= 30.0\ \text{kJ/g mol (insignificant error)}$$

Energy Balance Examples for Open, Steady-State Systems

Figure below shows a schematic of a heat exchanger in which a cold stream is used to cool a hot stream and a hot stream is used to warm a cold stream.



The cold water enters a header that feeds a number of tubes that carry the cold water through the heat exchanger. As the cold water flows through these tubes, heat is transferred through the walls of the tubes from the hot water to the cold water, thus increasing the temperature of the cold water and decreasing the temperature of the hot water. The hot water is added at the opposite end of the exchanger and flows back and forth past the tube bundle due to baffles inside the heat exchanger before exiting the exchanger near the cold water entrance. Assuming that the heat exchanger is properly insulated, the heat lost by the hot water is equal to the heat gained by the cold water, shown graphically in Figure below. Therefore, applying the heat balance equation (i.e., $\Delta H = Q$) to both the hot water system and the cold water system yields.

$$\dot{Q} = -F_{hw} C_p \Delta T_{hw}$$

$$\dot{Q} = F_{cw} C_p \Delta T_{cw}$$

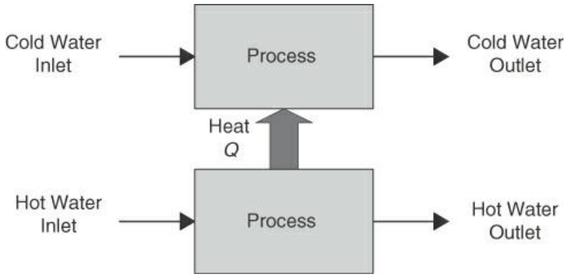
where F_{cw} and F_{hw} are the mass flow rate of the cold and hot water, C_p is the heat capacity of water, and ΔT_{cw} and ΔT_{hw} are the temperature changes through the process for the cold and hot water. Note that a minus sign appears in front of the hot water term in the preceding equation because the hot water temperature decreases as it flows through the exchanger.

If we perform an overall balance on the heat exchanger (i.e., $\Delta H = 0$) because the heat exchanger is insulated from its surroundings,

$$F_{cw} C_p \Delta T_{cw} + F_{hw} C_p \Delta T_{hw} = 0$$

Because the heat capacity of the hot water and the cold water are very nearly equal,

$$F_{cw} \Delta T_{cw} = -F_{hw} \Delta T_{hw}$$



From this equation, if the flow rate of the hot and cold water were equal, the magnitude of the temperature change of the hot and cold water would be the same. Furthermore, if the hot water flow rate were twice that of the cold water, the magnitude of the temperature change of the hot water would be half that of the cold water.

Strategy for solving energy balance problems

The general strategy for solving energy balance problems are listed in the following step:

- Choose the system, identify its boundary, and then decide whether the system is open or closed. Write the decision down. Change it if your first decision proves to be a poor one.
- Decide if the system is steady state or unsteady state. Write the decision down.
- Write down the general energy balance for the system (one for each system if you pick multiple systems) along with the other equations.

$$\Delta E = E_{t_2} - E_{t_1} = \sum_{\substack{\text{input}\\ \text{streams}\\ i=1}}^{M} m_i(\hat{H}_i + \widehat{KE}_i + \widehat{PE}_i) - \sum_{\substack{\text{output}\\ \text{streams}\\ o=1}}^{N} m_o(\hat{H}_o + \widehat{KE}_o + \widehat{PE}_o) + Q + W$$

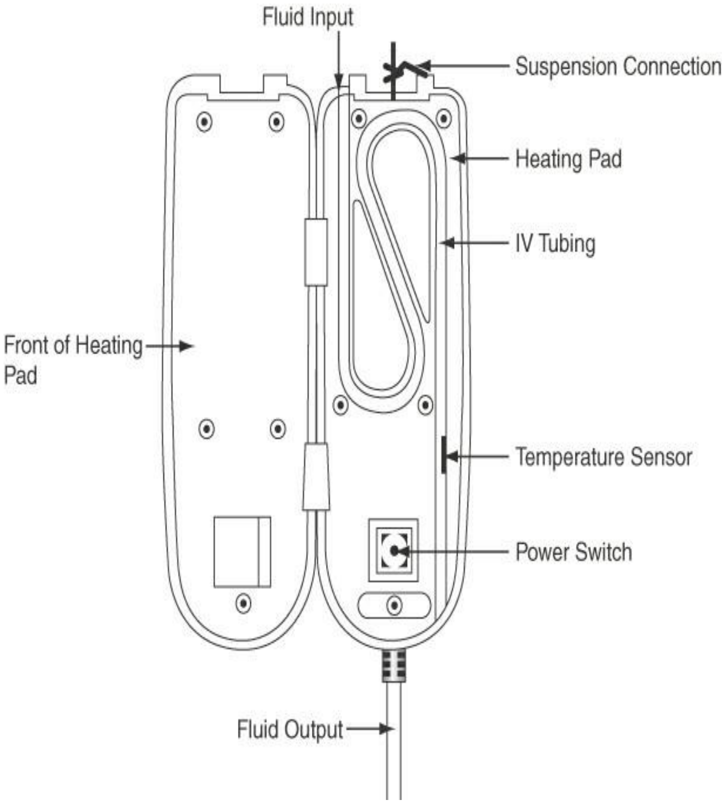
$$\Delta E = Q + W - \Delta(\hat{H} + \hat{K} + \hat{P})$$

- Simplify the general energy balance as much as possible by using information in the problem statement and reasonable assumptions based on your understanding of the process.
- Carry out a degree-of-freedom analysis that includes the energy balance as one equation (that may include more than one additional variable) along with the material balances.
- Choose a reference state for your calculations, usually the specification of temperature and pressure, but other variables may be substituted.

- Based on the reference state, get any needed physical property data (T, p, V, U, A) and add the values of the data to the sketch of the process. Be sure to include phase changes.
- Solve the energy balance alone or in conjunction with the material balances.

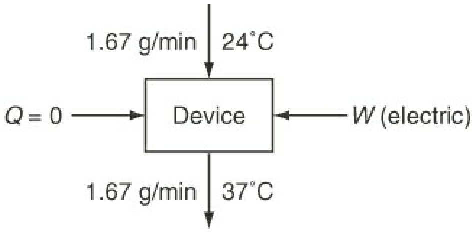
Example: Fluid Warmer

a fluid warmer that uses standard IV tubing instead of special disposable equipment. An electrically powered 250 W dry heat warmer supplies the heat transfer to the plastic tubing found in IV tube sets. The IV tubing is easily positioned in the S-shaped channel between the aluminum heating plates. The small size of the device permits a minimal length of tubing between the patient and the unit so that subsequent cooling of the exit fluid is negligible. The device warms up in 2 to 3 min, and then the fluid flows through the device at rates up to 12 cm3/min. Note that the temperature sensor after the fluid has passed through the heating section is used to adjust the power to the heating pad so that the desired temperature of the fluid is attained.



Acyclovir is an antiviral agent used for genital herpes (*Herpes simplex*) and shingles (varicella zoster, the chicken pox virus) by infusion through a vein. The solution flows through the warmer at the rate of 1.67 g/min of infusion solution. The entering fluid is at 24°C and exits at 37°C prior to infusion. The infusion solution in addition to the acyclovir contains 0.45% NaCl and 2.5% glucose. How many watts must be used by the warmer to warm the solution?

Solution



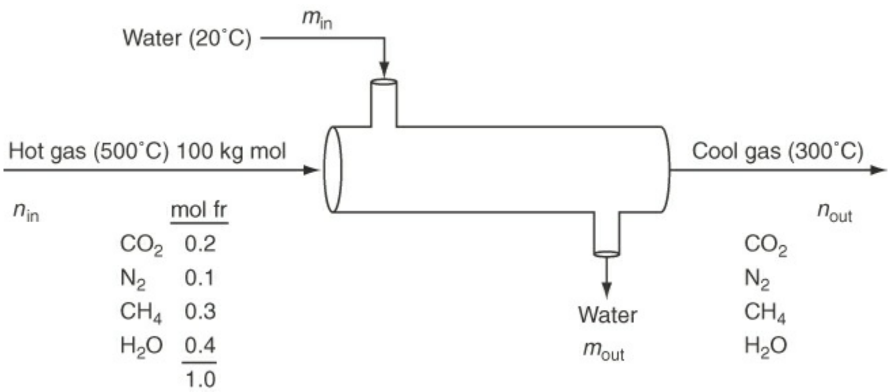
Choose the system and then the system is open, steady-state (except for a short warmup interval that we will ignore) system. If we consider the entire warming device, electrical work is involved. On the other hand, if we consider the warming device minus the electrical heater, the energy balance would be $\boldsymbol{\Delta H = Q}$, for which Q is the electrical heat provided by the heater:

$$Q=\Delta H_{\text{flow}}=FC_p\left(T_{\text{out}}-T_{\text{in}}\right)=\frac{1.67\text{ g}}{\text{min}}\Bigg|\frac{4.18\text{ J}}{(\text{g})(^\circ\text{C})}\Bigg|\frac{17^\circ\text{C}}{}\Bigg|\frac{1\text{ min}}{60\text{ s}}$$

$$=1.98\text{ J/s}\equiv 1.98\text{ W}$$

Example: Use of Combined Material and Energy Balances

Figure below shows a hot gas stream at 500°C being cooled to 300°C by transferring heat to the liquid water that enters at 20°C and exits at 213°C. Assume that the heat exchanger is insulated. The cooling water does not mix with the gas. Calculate the value of the flow rate of the water.



Solution

Basis: 100 kg mol of entering gas 1 ≡ min

$$\Delta H = Q = 0$$

Then $\Delta H = 0$ is the result, or in full:

$$\left[(n_{\text{gas}})(\hat{H}_{\text{gasout}}) + (m_{\text{water}})(\hat{H}_{\text{waterout}})\right] - \left[(n_{\text{gas}})(\hat{H}_{\text{gasin}}) + (m_{\text{water}})(\hat{H}_{\text{waterin}})\right] = 0$$

Rearrange to:

$$n_{\text{gas}} \Delta\hat{H}_{\text{gas}} - m_{\text{water}} \Delta\hat{H}_{\text{water}} = 0$$

$$n_{\text{gas component}} \left(\hat{H}_{\text{gas component at } 300^\circ\text{C}} - \hat{H}_{\text{gas component at } 500^\circ\text{C}}\right) \equiv n_i \Delta\hat{H}_i$$

Component	**$\Delta\hat{H}_i$ (kJ/kg mol)**	**n_i (kg mol)**	**$\Delta H = n_i \Delta\hat{H}_i$ (kJ)**
CO_2	−9333	20	−186,660
N_2	−6215	10	−62,150
CH_4	−11,307	30	−339,210
H_2O	−7441	40	−297,640
Total		100	$-885{,}660 = \Delta H_{\text{gas}}$

$$\begin{array}{cc} T\,(^\circ\text{C}) & \hat{H}\,(\text{kJ/kg}) \\ \hline \left.\begin{array}{cc} 20 & 35.7 \\ 213 & 391.8 \end{array}\right\} & \Delta\hat{H} = 350.1\ \text{kJ/kg} \end{array}$$

$$m_{\text{water}} = \frac{-\Delta H_{\text{gas}}}{\Delta\hat{H}_{\text{water}}} = \frac{-(-885{,}660)\ \text{kJ}}{350.1\text{kJ/kg}} = 2487\ \text{kg}$$

$$\dot{m}_{\text{water}} = 2487\ \text{kg/min} \qquad \text{(the basis was 1 min)}$$

Mechanical Energy Balances

Mechanical energy balances apply to steady-state cases in which heat transfer and thermal changes are not important (e.g., fluid flow applications), and the general energy balance becomes:

$$W = \Delta E_{\text{conv}}$$

For these cases, the following factors are considered: applied work, flow work, changes in kinetic energy, and changes in potential energy. Note that because the thermal changes are negligible, the enthalpy change reduces to the change in flow work, that is, $\Delta(pV)$. Therefore, the mechanical energy balance equation becomes:

$$\underset{\text{shaft work}}{W} = \underset{\text{change in kinetic energy}}{\Delta KE} + \underset{\text{change in potential energy}}{\Delta PE} + \underset{\text{change in flow work}}{\Delta(pV)}$$

Note that the change in kinetic energy, potential energy, and flow work are calculated as "out" minus "in." When flow work is considered as work done on the system by the surroundings, it is calculated as flow work in minus flow work out. As a result, the change in the flow work (i.e., out minus in) has a positive sign on the right side of above equation.

Mechanical Energy Balance Examples

Now that we have defined potential energy and kinetic energy, we can convert above equation into a form that can be directly used to solve mechanical energy balance problems:

$$W = \frac{1}{2}\dot{m}\Delta v^2 + \dot{m}g\Delta h + \frac{\dot{m}\Delta p}{\rho}$$

Where $\dot{m}$ is the mass flow rate through the system, $\Delta \upsilon$ is change in the velocity of a stream leaving and entering the system, Δh is the change in the elevation of a stream leaving and entering a system, and Δp is the pressure difference between the stream leaving and entering the system. The specific flow work is equal to $\hat{V}p = p/\rho$ so that the total change in flow work is equal to $\Delta(pV) = \dot{m}p/\rho$. This equation states that the work required is equal to the change in kinetic energy plus potential energy plus the flow work. Dividing through by $\dot{m}$ yields:

$$\frac{W}{\dot{m}} = \frac{1}{2}\Delta v^2 + g\Delta h + \frac{\Delta p}{\rho}$$

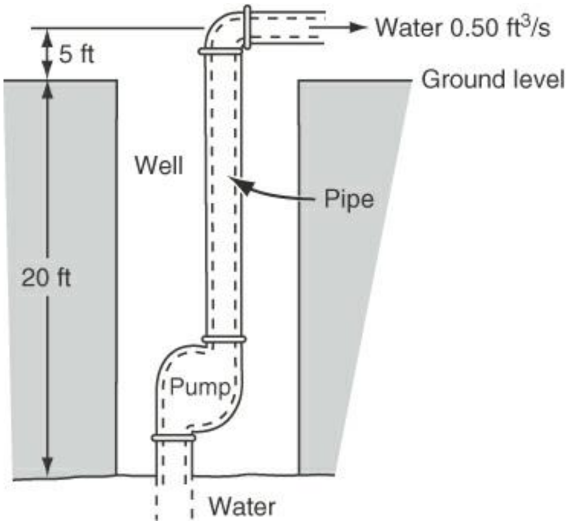
If no work is added to the system, flow through a system can result from an applied pressure drop across the system (i.e., Δ*p*). In that case, the following equation applies:

$$-\frac{\Delta p}{\rho}=\frac{1}{2}\Delta v^2+g\Delta h$$

Note that because Δ*p* is outlet pressure minus the inlet pressure, when pressure is used to drive flow through a system, Δ*p* is negative, thus the minus sign. This equation is known as **Bernoulli's equation**.

Example: Calculation of the Power Needed to Pump Water in an Open, Steady-State System

Water is pumped from a well in which the water level is a constant 20 ft below the ground level. The water is discharged into a level pipe that is 5 ft above the ground at a rate of 0.50 ft³/s. Assume that negligible heat transfer occurs from the water during its flow. Calculate the electric power required by the pump if it is 100% efficient; you can neglect friction in the pipe and the pump.



Solution

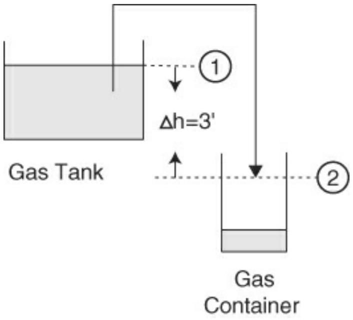
the pipe from the water level in the well to the place where the water that exits is at 5 ft above the ground so that the pump is included. Because of a steady-state system and the pipe diameter appears to be the same for both the inlet and the exit, Δ*KE* = 0. Also, the pressure at the exit is equal to the pressure at the inlet. After these simplifications, Equation of grneral mechanical energy becomes:

$$\frac{W}{\dot{m}}=g\Delta h$$

$$W=\frac{0.5\,\text{ft}^3}{\text{s}}\left|\frac{62.4\ \text{lb}_\text{m}\text{H}_2\text{O}}{\text{ft}^3}\right|\frac{32.2\ \text{ft}}{\text{s}^2}\left|\frac{25\ \text{ft}}{}\right|\frac{(\text{s}^2)(\text{lb}_\text{f})}{32.2(\text{ft})(\text{lb}_\text{m})}\left|\frac{\text{hp-s}}{550(\text{lb}_\text{f})(\text{ft})}\right.=1.42\ \text{hp}$$

Example: Siphoning Gasoline

Assume that you want to siphon gasoline out of your gas tank using a hose with a 0.5 in. inside diameter. Determine the flow rate of gasoline in gallons per minute based on the arrangement shown in Figure neglecting the friction between the gasoline and the hose.



Solution

Simplifying Equation of mechanical energy (1) the pressure at the entrance and exit for this system will both be atmospheric pressure, so the flow work should be zero; and (2) no work is applied to this system. Therefore, the mechanical energy balance equation reduces to

$$0 = \frac{1}{2}\Delta v^2 + g\Delta h$$

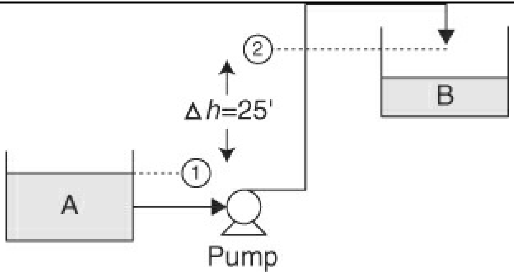
Solving for the exit velocity, assuming the entrance velocity (i.e., the velocity of the gasoline level in the gas tank) is zero,

$$v = \sqrt{2g\Delta h} = \sqrt{\frac{2}{} \left| \frac{32.2\ \text{ft}}{\text{s}^2} \right| \frac{2\ \text{ft}}{}} = 11.35\ \text{ft/s}$$

$$Q = Av = \frac{\pi}{} \left| \frac{(0.5\ \text{in})^2}{4} \right| \frac{11.35\ \text{ft}}{\text{s}} \left| \frac{\text{ft}^2}{(12\ \text{in})^2} \right| \frac{7.481\ \text{gal}}{\text{ft}^3} \left| \frac{60\ \text{s}}{\text{min}} \right. = 6.947\ \text{gpm}$$

Example: Determine the Flow Rate through a Piping System with a Pump

Determine the work done for the system in hp shown in Figure below in gpm. Assume that the fluid being pumped is water, the flow rate from tank A to tank B through this system is 0.3151 ft^3/s. and the pipes in this system have a 2 in. inside diameter; neglect the friction in the pipes and the pump.



Solution

Simplifying Equation of mechanical energy balance the pressure at the entrance and exit for this system will both be atmospheric pressure, so the flow work should be zero. Therefore, the mechanical energy balance equation reduces to:

$$\frac{W}{\dot{m}}=\frac{1}{2}\Delta v^2+g\Delta h$$

Note $\dot{m}$ that and υ are both depend on the flow rate Q between the tanks: and $\dot{m}=\rho Q$ $\upsilon = Q/A$, where A is the cross-sectional areas of the pipe between the tanks. Therefore, the previous equation becomes:

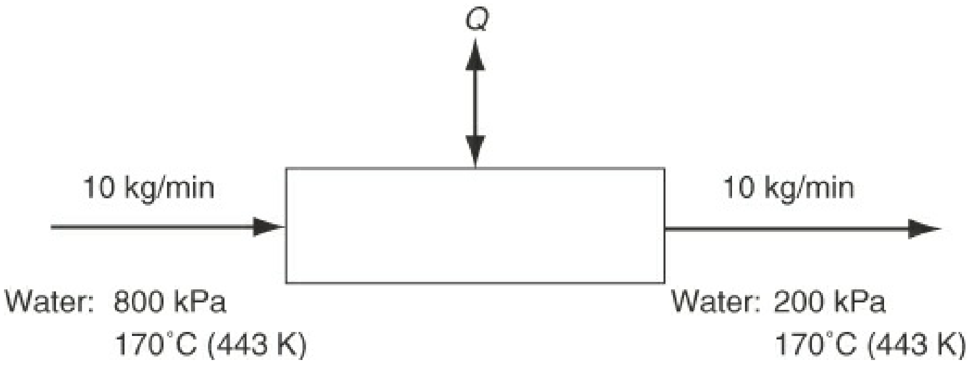
$$\frac{W}{Q\rho}=\frac{Q^2}{2A^2}+g\Delta h$$

$$\frac{\text{W hp}}{}\left|\frac{\text{ft}^3}{62.4\ \text{lb}_\text{m}}\right|\frac{\text{s}}{0.3151\ \text{ft}^3}\left|\frac{550\ \text{ft Ib}_\text{m}}{\text{hp-s}}\right|\frac{32.2\ \text{ft Ib}_\text{m}}{\text{Ib}_\text{f}\ \text{s}^2}\Bigg|=900.7\ \text{ft}^2/\text{s}^2=\frac{2\times(0.3151)^2\ \text{ft}^6}{\text{s}^2}\left|\frac{}{\left(\frac{\Pi}{4}\left(\frac{2\ \text{in}}{}\times\frac{\text{ft}}{12\ \text{in}}\right)^2\right)^2}\right|$$

W=0.25 hp

Problem

1. Calculate Q for the system shown in Figure below in kJ/min



2. Consider a steam heat exchanger in which 500 gallons per minute (gpm) of water are heated from 65°F to 150°F using 50 psig steam. Assume that the steam condenses to saturated liquid at 50 psig. What is the required flow rate of steam for this heat exchang.
3. A horizontal frictionless piston-cylinder contains 10 lb of liquid water saturated at 320°F. Heat is now transferred to the water until one-half of the water vaporizes. If the piston moves slowly to do work against the surroundings, calculate the work done by the system (the piston-cylinder) during this process.
4. Calculate the heat transfer to the atmosphere per second from a circular pipe, 5 cm in diameter and 100 m long, carrying steam at an average temperature of 120°C if the surroundings are at 20°C. The heat transfer can be estimated from the relation

   $$Q = hA\Delta T$$

   where $h = 5$ J/(s)(m^2)(°C) A is the surface area of the pipe ΔT is the temperature difference between the surface of the pipe and ambient conditions
5. Steam is used to cool a polymer reaction. The steam in the steam chest of the apparatus is found to be at 250.5°C and 4000 kPa absolute during a routine measurement at the beginning of the day. At the end of the day the measurement showed that the temperature was 650°C and the pressure 10,000 kPa absolute. What was the internal energy change of 1 kg of steam in the chest during the day? Obtain your data from the steam tables.
6. Estimate ΔH ν for n-heptane at its normal boiling point given $T_b = 98.43$°C, $T_c = 540.2$ K, $p_c = 27$ atm. Use Chen's equation. Calculate the percent error in this value compared to the tabulated value of 31.69 kJ/g mol.

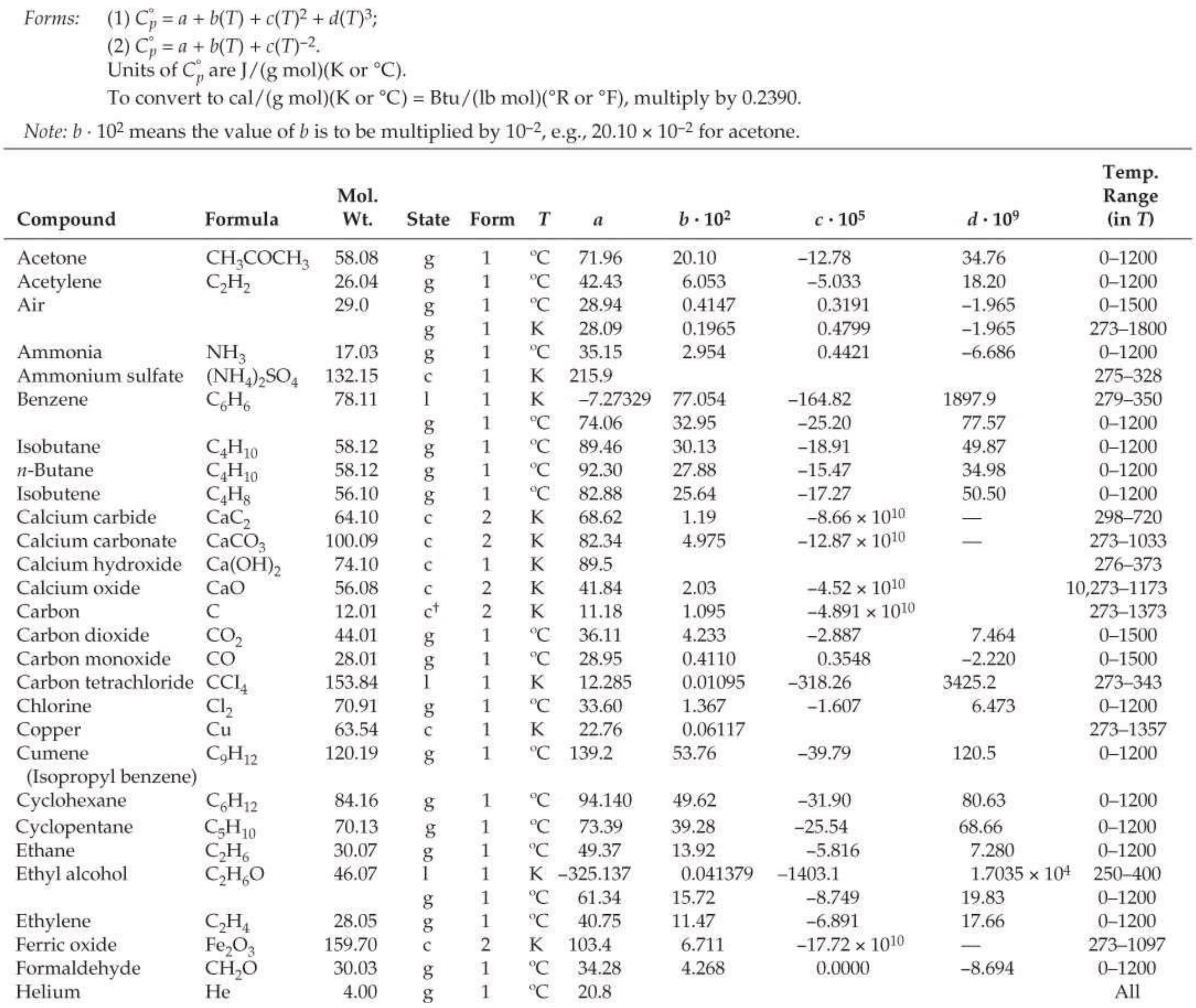
7. Two gram moles of nitrogen are heated from 50°C to 250°C in a cylinder. What is ΔH for the process? The heat capacity equation is:

$$C_p = 27.32 + 0.6226 \times 10^{-2} T - 0.0950 \times 10^{-5} T^2$$

where T is in kelvin and C_p is in J/(g mol)(°C).

8. The calculate the electric power required (in kilowatt-hours) to heat all of an aluminum wire (positioned in a vacuum similar to a lightbulb filament) from 25°C to 660°C (liquid) to be used in a vapor deposition apparatus. The melting point of Al is 660°C. The wire is 2.5 mm in diameter and has a length of 5.5 cm. (The vapor deposition occurs at temperatures in the vicinity of 900°C.) Data: For Al, Cp = 20.0 + 0.0135T, where T is in kelvin and Cp is in J/(g mol)(°C). The ΔH_{fusion} = 10,670 J/(g mol)(°C) at 660°C. The density of Al is 19.35 g/cm^3.
9. The world's largest plant that obtains energy from tidal changes is at Saint-Malo, France. The plant uses both the rising and falling cycles (one period in or out is 6 hr 10 min in duration). The tidal range from low to high is 14 m, and the tidal estuary (the Rance River) is 21 km long with an area of 23 km2. Assume that the efficiency of the plant in converting potential to electrical energy is 85%, and estimate the average power produced by the plant. (Note: Also assume that after high tide, the plant does not release water until the sea level drops 7 m, and after a low tide it does not permit water to enter the basin until the level outside the basin rises 7 m, and the level differential is maintained during discharge and charge.)
10. Calculate the enthalpy change in heating 1 g mol of CO_2 from 50°C to 100°C at 1 atm. Do this problem by three different methods:
    a. Use the heat capacity equation.
    b. Use the CO_2 chart.
    c. Use the table of combustion gases.

The heat capacity equation



Forms: (1) $C_p^\circ = a + b(T) + c(T)^2 + d(T)^3$;

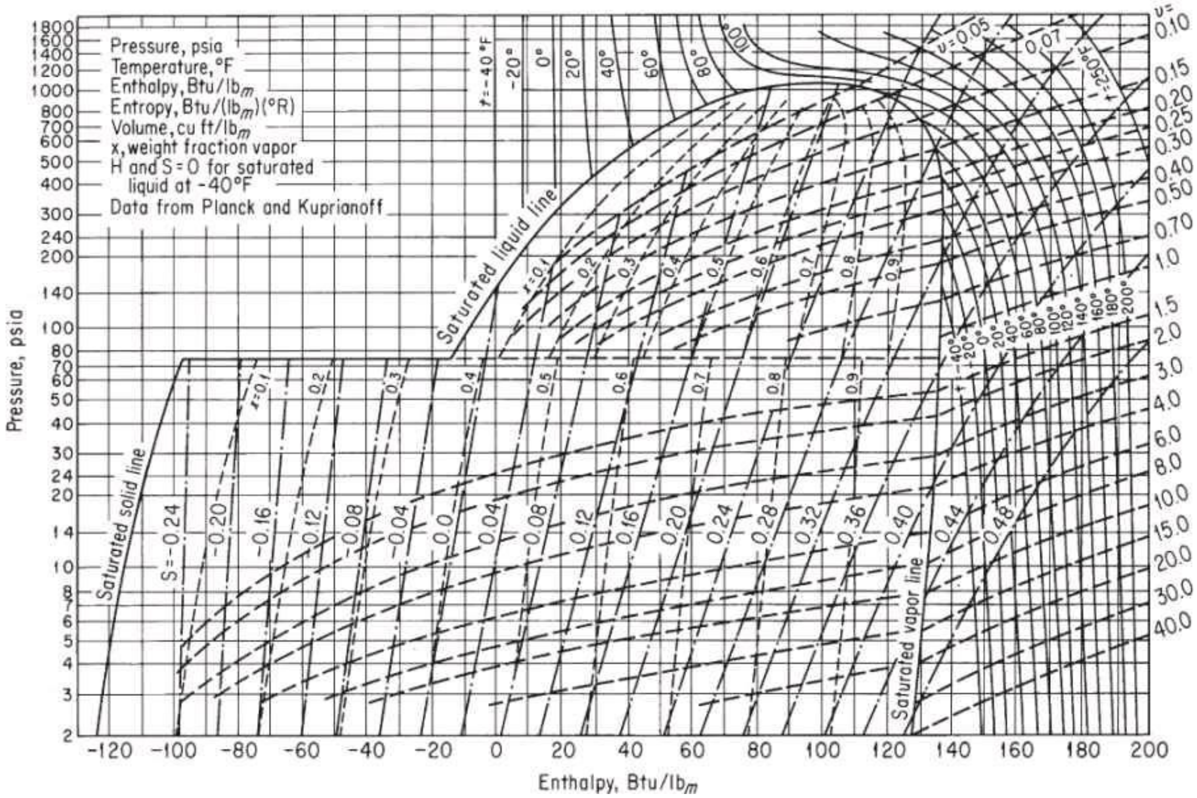
(2) $C_p^\circ = a + b(T) + c(T)^{-2}$.

Units of C_p° are J/(g mol)(K or °C).

To convert to cal/(g mol)(K or °C) = Btu/(lb mol)(°R or °F), multiply by 0.2390.

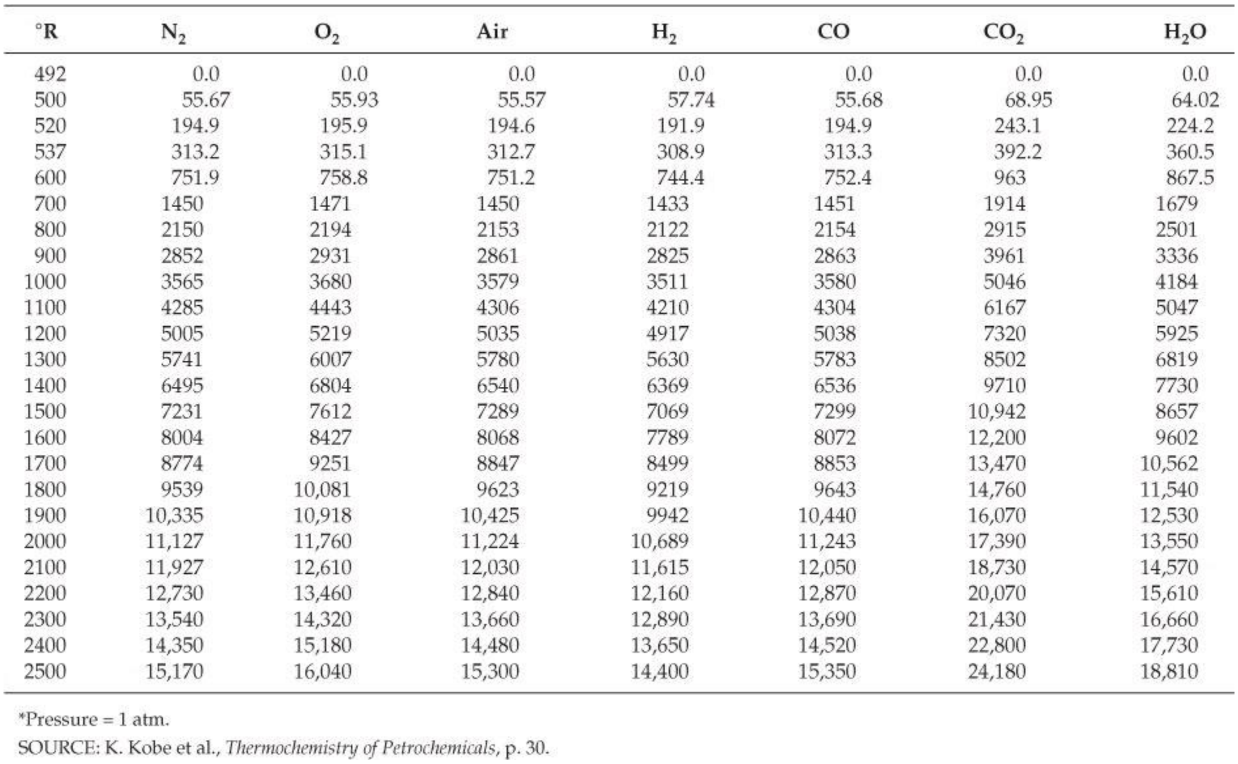
Note: $b \cdot 10^2$ means the value of b is to be multiplied by 10^{-2}, e.g., 20.10×10^{-2} for acetone.

Compound	Formula	Mol. Wt.	State	Form	*T*	*a*	$b \cdot 10^2$	$c \cdot 10^5$	$d \cdot 10^9$	Temp. Range (in *T*)
Acetone	CH_3COCH_3	58.08	g	1	°C	71.96	20.10	–12.78	34.76	0–1200
Acetylene	C_2H_2	26.04	g	1	°C	42.43	6.053	–5.033	18.20	0–1200
Air		29.0	g	1	°C	28.94	0.4147	0.3191	–1.965	0–1500
			g	1	K	28.09	0.1965	0.4799	–1.965	273–1800
Ammonia	NH_3	17.03	g	1	°C	35.15	2.954	0.4421	–6.686	0–1200
Ammonium sulfate	$(NH_4)_2SO_4$	132.15	c	1	K	215.9				275–328
Benzene	C_6H_6	78.11	l	1	K	–7.27329	77.054	–164.82	1897.9	279–350
			g	1	°C	74.06	32.95	–25.20	77.57	0–1200
Isobutane	C_4H_{10}	58.12	g	1	°C	89.46	30.13	–18.91	49.87	0–1200
n-Butane	C_4H_{10}	58.12	g	1	°C	92.30	27.88	–15.47	34.98	0–1200
Isobutene	C_4H_8	56.10	g	1	°C	82.88	25.64	–17.27	50.50	0–1200
Calcium carbide	CaC_2	64.10	c	2	K	68.62	1.19	-8.66×10^{10}	—	298–720
Calcium carbonate	$CaCO_3$	100.09	c	2	K	82.34	4.975	-12.87×10^{10}	—	273–1033
Calcium hydroxide	$Ca(OH)_2$	74.10	c	1	K	89.5				276–373
Calcium oxide	CaO	56.08	c	2	K	41.84	2.03	-4.52×10^{10}		10,273–1173
Carbon	C	12.01	c†	2	K	11.18	1.095	-4.891×10^{10}		273–1373
Carbon dioxide	CO_2	44.01	g	1	°C	36.11	4.233	–2.887	7.464	0–1500
Carbon monoxide	CO	28.01	g	1	°C	28.95	0.4110	0.3548	–2.220	0–1500
Carbon tetrachloride	CCl_4	153.84	l	1	K	12.285	0.01095	–318.26	3425.2	273–343
Chlorine	Cl_2	70.91	g	1	°C	33.60	1.367	–1.607	6.473	0–1200
Copper	Cu	63.54	c	1	K	22.76	0.06117			273–1357
Cumene (Isopropyl benzene)	C_9H_{12}	120.19	g	1	°C	139.2	53.76	–39.79	120.5	0–1200
Cyclohexane	C_6H_{12}	84.16	g	1	°C	94.140	49.62	–31.90	80.63	0–1200
Cyclopentane	C_5H_{10}	70.13	g	1	°C	73.39	39.28	–25.54	68.66	0–1200
Ethane	C_2H_6	30.07	g	1	°C	49.37	13.92	–5.816	7.280	0–1200
Ethyl alcohol	C_2H_6O	46.07	l	1	K	–325.137	0.041379	–1403.1	1.7035×10^4	250–400
			g	1	°C	61.34	15.72	–8.749	19.83	0–1200
Ethylene	C_2H_4	28.05	g	1	°C	40.75	11.47	–6.891	17.66	0–1200
Ferric oxide	Fe_2O_3	159.70	c	2	K	103.4	6.711	-17.72×10^{10}	—	273–1097
Formaldehyde	CH_2O	30.03	g	1	°C	34.28	4.268	0.0000	–8.694	0–1200
Helium	He	4.00	g	1	°C	20.8				All



Pressure-enthalpy chart for carbon dioxide

Enthalpies of Combustion Gases* (Btu/lb mol)

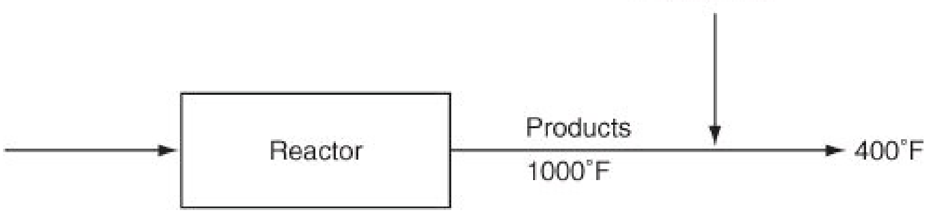


°R	N_2	O_2	Air	H_2	CO	CO_2	H_2O
492	0.0	0.0	0.0	0.0	0.0	0.0	0.0
500	55.67	55.93	55.57	57.74	55.68	68.95	64.02
520	194.9	195.9	194.6	191.9	194.9	243.1	224.2
537	313.2	315.1	312.7	308.9	313.3	392.2	360.5
600	751.9	758.8	751.2	744.4	752.4	963	867.5
700	1450	1471	1450	1433	1451	1914	1679
800	2150	2194	2153	2122	2154	2915	2501
900	2852	2931	2861	2825	2863	3961	3336
1000	3565	3680	3579	3511	3580	5046	4184
1100	4285	4443	4306	4210	4304	6167	5047
1200	5005	5219	5035	4917	5038	7320	5925
1300	5741	6007	5780	5630	5783	8502	6819
1400	6495	6804	6540	6369	6536	9710	7730
1500	7231	7612	7289	7069	7299	10,942	8657
1600	8004	8427	8068	7789	8072	12,200	9602
1700	8774	9251	8847	8499	8853	13,470	10,562
1800	9539	10,081	9623	9219	9643	14,760	11,540
1900	10,335	10,918	10,425	9942	10,440	16,070	12,530
2000	11,127	11,760	11,224	10,689	11,243	17,390	13,550
2100	11,927	12,610	12,030	11,615	12,050	18,730	14,570
2200	12,730	13,460	12,840	12,160	12,870	20,070	15,610
2300	13,540	14,320	13,660	12,890	13,690	21,430	16,660
2400	14,350	15,180	14,480	13,650	14,520	22,800	17,730
2500	15,170	16,040	15,300	14,400	15,350	24,180	18,810

*Pressure = 1 atm.

SOURCE: K. Kobe et al., *Thermochemistry of Petrochemicals*, p. 30.

11. Wet steam flows in a pipe at a pressure of 700 kPa. To check the quality, the wet steam is expanded adiabatically to a pressure of 100 kPa in a separate pipe. A thermocouple inserted into the pipe indicates that the expanded steam has a temperature of 125°C. What was the quality of the wet steam in the pipe prior to expansion?
12. A large high-pressure tank contains 10 kg of steam. In spite of the insulation on the tank it loses 2050 kJ/hr to the surroundings. How many kilowatts are needed to maintain the steam at 3000 kPa and 600 K?
13. Air is being compressed from 100 kPa and 255 K (where it has an enthalpy of 489 kJ/kg) to 1000 kPa and 278 K (where it has an enthalpy of 509 kJ/kg). The exit velocity of the air from the compressor is 60 m/s. What is the power required (in kilowatts) for the compressor if the load is 100 kg/hr of air?
14. Hot reaction products (assume they have the same properties as air) at 1000°F leave a reactor. In order to prevent further reaction, the process is designed to reduce the temperature of the products to 400°F by immediately spraying liquid water into the gas stream.



How many pounds of water at 70°F are required per 100 lb of products leaving at 400°F? For this problem you do not have to get a numerical solution. Instead, list the following in this order:

a. State what the system you select is.
b. Specify open or closed.
c. Draw a picture.
d. Put all the known or calculated data on the picture in the proper places.
e. Write down the material and energy balances (use the symbols in the text) and simplify them as much as possible; list each assumption in so doing.
f. Insert the known data into the simplified equation(s) you would use to solve the problem.