

Engineering Thermodynamics

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Contents

1 July 5, 2017	2
1.1 Thermodynamics	2
2 July 7, 2017	2
2.1 Properties	2
3 July 10, 2017	3
3.1 Systems	3
4 July 12, 2017	4
4.1 Gibb's Phase Rule	4
4.2 Temperature	4
4.3 Pressure	4
5 July 14, 2017	5
5.1 Energy	5
5.2 Energy Transfer Across the System Boundary	6
5.3 Modes of Heat Transfer	6
6 July 17, 2017	7
6.1 Work at a Moving Boundary	7
7 July 19, 2017	7
7.1 Work Examples	7
7.2 Types of Processes	9
8 July 28, 2017	9
8.1 Property Table Examples	9

§1 July 5, 2017

§1.1 Thermodynamics

Thermodynamics is a branch of science which deals with equilibrium processes involving heat and work. In thermodynamics, rates are not considered. Thermodynamics constrains all processes, as it sets the limits of a system's performance.

In a closed system, we refer to the gas as a **control mass**. A force could be applied to the control mass, which is encapsulated by a **system boundary**.

Open systems on the other hand, includes pumps, turbines, compressors, refrigerators, and valves. An open system such as a water heater would have F_{in} , T_{in} , F_{out} , and T_{out} . Both mass and energy can cross the system boundary in an open system. The open systems we will consider will be assumed to operate in **steady-state**. That is, the accumulation term in the mass or energy balance will be zero, since it will not change with time.

Below are conversions between common temperature units:

- $T(K) = T(^{\circ}C) + 273.15$.
- $T(R) = T(^{\circ}F) + 459.67$.
- $T(^{\circ}F) = 1.8 \cdot T(^{\circ}C) + 32$.
- $-273.15^{\circ}C = -459.67^{\circ}F = 0K = 0R$.
- $\Delta T(K) = \Delta T(^{\circ}C)$.
- $\Delta T(R) = \Delta T(^{\circ}F)$.

§2 July 7, 2017

§2.1 Properties

Properties are independent of path. In other words, properties are independent of history. For instance, work and heat depend on how the process works. Thus, they are path dependent and are not properties. Some examples of properties include volume, temperature, pressure, mass, internal energy, enthalpy, and entropy. Properties can be further classified as intensive or extensive:

- **Intensive Properties** are independent of size. Examples include temperature and pressure. Intensive properties are usually lowercase (except temperature and pressure).
- **Extensive Properties** are dependent upon the size of the system. For example, length, mass, and volume are extensive properties. Extensive properties are usually uppercase (except mass).

To determine whether a property is intensive or extensive, we can divide the system into two equal parts with an imaginary split. Each part will have the same value of intensive properties as the original system, but only half the initial value of the extensive properties.

Specific properties are extensive properties divided by mass. For single phase systems, specific properties are also intensive. Examples include specific volume, specific enthalpy, specific internal energy, and specific entropy.

Remark 2.1. Specific gravity is the density of a substance divided by the density of water.

§3 July 10, 2017

§3.1 Systems

A **system** defines the volume in space in which we are applying our analysis. The boundary of the system is arbitrary. However, some choices may simplify analysis. There are three types of systems:

1. **Open Systems:** Mass and energy can cross the system boundary. Mass can flow in and out. Work is done by the surroundings on the system.
2. **Closed Systems:** Mass cannot leave the system, but energy can. Pistons and cylinders are examples of closed systems.
3. **Isolated Systems:** Neither mass nor energy can cross the system boundary.

The **state** is the value of a system's properties at any given moment. A **process** occurs when there is a change in the state. When a process starts and finishes at the same state, we have a **cycle**. There are different types of processes:

- **Isothermal:** The process occurs at a constant temperature. This usually requires adding or removing heat.
- **Isobaric:** The process occurs at a constant pressure. This can be done with a floating piston. We can perform a force balance,

$$P_{gas}A = mg + P_{atm}A,$$

where P_{gas} is the pressure of the gas, A is the cross sectional area of the piston, m is the mass of the piston, and P_{atm} is the atmospheric pressure.

- **Isochoric:** The process occurs at a constant volume. These occur in rigid vessels. **Rigid vessels** are ones that maintain their shapes during a process.
- **Adiabatic:** The process occurs without heat transfer to or from the system. Adiabatic processes are implied with terms such as **well insulated**. These never occur at a constant temperature.

In thermodynamics, we are concerned with processes that reach a state of equilibrium. In other words, these are processes whose states are independent of time. We will focus on the following types of equilibrium:

- **Mechanical Equilibrium:** The pressure is constant.
- **Thermal Equilibrium:** The temperature is constant.
- **Phase Equilibrium:** There is no tendency for the mass of phases to change.
- **Chemical Equilibrium:** Forward and reverse reactions occur at the same rate.

In theory, attaining equilibrium requires infinite time. However, if a process only deviates from equilibrium by a small amount, we say that we have a **quasi-equilibrium state**. For the sake of our analyses, we will take this to be the **equilibrium state**.

§4 July 12, 2017

§4.1 Gibb's Phase Rule

We recall **Gibb's Phase Rule**,

$$F = C - P + 2,$$

where F is the degrees of freedom, C is the number of components, and P is the number of phases in thermodynamic equilibrium with each other. We can have multiple liquid and solid phases, but only one gas phase. The degrees of freedom indicate the number of intensive properties that can be specified independently. The phase rule can be used to determine whether enough information has been given to solve a problem.

§4.2 Temperature

Sensory perception is an unreliable means of measuring temperature. **Temperature** is formally introduced using the **Zeroth Law of Thermodynamics**. If we replace a body in thermal equilibrium with another, with a device whose properties can be correlated with temperature, we obtain a reliable means of measuring temperature.

§4.3 Pressure

We define **pressure** as the force normal to the surface divided by the area of the surface,

$$P = \frac{F}{A}.$$

The most common units for pressure are:

- **Pascal (Pa)**: $1Pa = 1N/m^2$.
- **bar (bar)**: $1bar = 10^5Pa$.
- **atmosphere (atm)**: $1atm = 101.325kPa$.
- **Pounds per Square Inch (psi)**: $psia$ is absolute pressure (gauge and atmosphere), while $psig$ is gauge pressure. We should only use psi for relative pressure ΔP . $14.696psia = 1atm$.

In measuring pressure, it simplifies the instrument design if we can neglect atmospheric pressure since it varies with location. We can then define gauge pressure as the absolute pressure minus the atmospheric pressure. In this course, all pressures will be absolute unless specified otherwise.

Any property that changes with respect to pressure can be correlated with pressure. At the bottom of a liquid column of height h , the pressure is given by $P_{bottom} = \rho gh$. If the pressure at the top of the column is non-zero, then we add the pressure at the top of the column to obtain $P_{bottom} = P_{top} + \rho gh$. To use a manometer to measure pressure, we note that the side that pushes further the liquid inside has the higher pressure. We can use ρgh to determine the pressure differential where h is the difference in the height of the liquid on either side of the **U-tube manometer**.

Example 4.1

Calculate the height of water such that the pressure difference is $100kPa$, given that $g = 9.81m/s^2$ and $\rho = 10^3kg/m^3$.

We find that the height is $10.19m$.

Example 4.2

A manometer is attached to a tank of gas with a pressure greater than atmospheric pressure at $93kPa$. The manometer fluid is mercury, with a density of $\rho = 13.59g/cm^3$. The height difference across the manometer is $2cm$. Determine the gauge pressure and the absolute pressure.

We recall that h is the height difference within the manometer. First, the gauge pressure is the reading of the manometer. The absolute pressure is obtained by adding the atmospheric pressure to the gauge pressure. With a height difference of $2cm$, we find that the gauge pressure is given by

$$P_{gauge} = \rho g(h_3 - h_2) = (13590)(9.81)(.02) = 2666Pa.$$

Therefore, the absolute pressure is given by

$$P = P_{atm} + P_{gauge} = 93000 + 2666 = 95666Pa.$$

Because of the insignificance of gas density, the gas contribution (calculated using the density of gas, the acceleration due to gravity, and the change in height) is often neglected. Note also that the height used to calculate pressure is always the vertical height, even in problems with inclined manometers. When there is more than one fluid in a manometer, we denote the interface pressure as P_{int} . We can then sum the contributions of the different fluids to determine the overall pressure.

§5 July 14, 2017

§5.1 Energy

The **First Law of Thermodynamics** is the conservation of energy equation. This states that the energy change within a system is equal to the net energy transferred across the system boundary. This is given by

$$\Delta E_{universe} = \Delta E_{system} + \Delta E_{surroundings} = 0,$$

where ΔE_{system} is the energy change of the system, $\Delta E_{surroundings}$ is the energy change of the system, and the universe is the system with the surroundings.

The energy of the system and surroundings may change in a variety of ways. **Stored energy** refers to the energy change within the system:

- **Kinetic Energy:** This is the energy due to motion, relative to a particular member. For specific kinetic energy, we divide by mass.
- **Potential Energy:** This is the energy due to a relative position. For specific potential energy, we divide by mass.
- **Internal Energy:** This is the summation of all of the molecule-scaled energies. This is caused by translations, rotations, and vibrations. Internal energy can be found from tabulated data, or from invoking the **Ideal Gas Law**. We use U to denote the extensive internal energy, and u to denote the specific internal energy.

Given the preceding cases of stored energy, the energy change of the system is

$$\Delta E_{system} = \Delta KE + \Delta PE + \Delta U.$$

§5.2 Energy Transfer Across the System Boundary

Energy transfer across a system boundary can occur via heat and work. Heat transfer is energy that is exchanged due to a temperature difference across a system boundary. Energy that flows across a system boundary by means other than a temperature difference is called work. By convention, work is positive when it is done by the system on the surroundings.

Example 5.1

Examples of positive work done by the system on the surroundings include car engines and plane turbines. Examples of negative work done by the surroundings on the system include compressors and battery charging.

Heat transfer on the other hand, is positive when it is directed into the system. Heat always flows from a higher temperature to a lower temperature. Heat and work are collectively referred to as **transitory energy**, as opposed to stored energy. Heat and work cannot be stored, and can only be defined at the system boundary. The net energy transferred across the system boundary is

$$\Delta E_{\text{boundary}} = -\Delta E_{\text{surroundings}} = Q - W.$$

Therefore, the first law can be stated for a closed system, where

$$Q - W = \Delta KE + \Delta PE + \Delta U.$$

§5.3 Modes of Heat Transfer

There are three primary ways that heat could transfer:

1. **Conduction:** Heat transfer between two stationary objects which are in perfect contact with each other is conductive. Conductive heat transfer is computed using **Fourier's Law**,

$$Q = -kA \frac{dT(x)}{dx},$$

where Q is the heat flow in W , k is the thermal conductivity in $W/m \cdot K$, A is the area normal to the heat flow in m^2 , x is the distance in m . and T is the temperature in K . The negative sign arises because heat flows from a higher temperature to a lower temperature.

2. **Convection:** Convective heat transfer arises due to fluid motion. It is computed using **Newton's Law of Cooling**,

$$Q = hA\Delta T,$$

where h is the convective heat transfer coefficient in W/m^2K , A is the surface area exposed between for heat exchange in m^2 , and ΔT is the change in temperature in K .

3. **Radiation:** Radiative heat transfer is due to electromagnetic energy. The rate of heat transfer is proportional to T^4 .

§6 July 17, 2017

§6.1 Work at a Moving Boundary

There are different modes of work: There are different modes of work. This could take the form of a horizontal piston in which a pressure of P_{gas} pushes the piston a distance of x . Since the movement is in the direction of force, we have

$$W = \int_{x_1}^{x_2} F_{gas} dx = \int_{x_1}^{x_2} P_{gas} A dx = \int_{V_1}^{V_2} P_{gas} dV,$$

where V is the extensive volume in m^3 . However, we need a relationship between P and V to calculate W .

- Isochoric System: V is constant, so $dV = 0$. Therefore,

$$W = \int_{V_1}^{V_2} P dV = 0.$$

- Isobaric System: P is constant. Therefore,

$$W = \int_{V_1}^{V_2} P dV = P \int_{V_1}^{V_2} dV = P \Delta V.$$

- Polytropic Process: $PV^n = C$, where n is an empirical (experimentally derived) constant, and C is a constant. This is the process path imposed by external forces. It is independent of any equation of state (such as the ideal gas law). When one has experimental data for P versus V , the value of n can be found by plotting,

$$\ln(P) = -n \ln(V) + \ln(C).$$

Therefore, we can derive an expression for work,

$$W = \int_{V_1}^{V_2} P dV = \int_{V_1}^{V_2} \frac{C}{V^n} dV = \frac{1}{1-n} (P_2 V_2 - P_1 V_1).$$

This is valid for all fluids. For an ideal gas, we have $PV = mRT$, where R is the gas constant such that the molecular weight multiplied by R equals the universal gas constant R_u . Thus, only for ideal gases in a closed system, this can be expressed as,

$$W = \frac{mR}{1-n} (T_2 - T_1).$$

In this course, R is the specific gas constant with units J/kgK . The universal gas constant R_u has units $J/molK$.

§7 July 19, 2017

§7.1 Work Examples

Example 7.1

The pressure in a 0.2m^3 cylinder of propane at 300K is 100kPa . At 240K , determine the mass of the propane in the cylinder, the final pressure, the final volume, and the work during this process. $PV^{1.1}$ is constant.

Solution. Since $PV^{1.1}$ is constant, this implies that $n = 1.1$. To find the mass of propane, we will assume that propane is an ideal gas, so $m = PV/RT$. Thus,

$$\frac{P_1 V_1}{RT_1} = \frac{P_2 V_2}{RT_2},$$

since $m_1 = m_2$. This equation relates the pressure and volume within the fluid. $PV^{1.1} = C$ is external upon the fluid. This is how the system goes from the first state to the second state. For an ideal gas undergoing a polytropic process, recall that $W = (P_2 V_2 - P_1 V_1)/(n - 1)$. Also recall the first law of thermodynamics, which states that $Q - W = \Delta KE + \Delta PE + \Delta U$. This gives us

$$m = \frac{P_1 V_1}{RT_1} = \frac{(100 \cdot 10^3 \text{Pa}) (0.2\text{m}^2)}{(188.5\text{J/kg})(300\text{K})} = 0.3537\text{kg}.$$

To find P_2 , it is known that $P_1 V_1^{1.1} = P_2 V_2^{1.1}$. From the ideal gas law, we can equate $P_1 V_1/T_1$ with the values for pressure, volume, and temperature at the second state. Thus, we obtain

$$\begin{aligned} \frac{T_2}{T_1} &= \left(\frac{P_2}{P_1} \right)^{1-\frac{1}{n}}, \\ \frac{V_2}{V_1} &= \left(\frac{T_2}{T_1} \right)^{\frac{1}{1-n}}. \end{aligned}$$

Solving the first equation for P_2 , we find that

$$P_2 = P_1 \left(\frac{T_2}{T_1} \right)^{\frac{n}{n-1}} = (100\text{kPa}) \left(\frac{340\text{K}}{300\text{K}} \right)^{\frac{1.1}{0.1}} = 396\text{kPa}.$$

To find V_2 , we apply the second equation to find that

$$V_2 = V_1 \left(\frac{T_2}{T_1} \right)^{\frac{1}{1-n}} = (0.2\text{m}^2) \left(\frac{340}{300} \right)^{-10} = 0.0572\text{m}^3.$$

Finding the work done, we use the equation for polyprotic processes,

$$W = \frac{1}{1-n} (P_2 V_2 - P_1 V_1) = \frac{1}{1-1.1} ((396 \cdot 10^3 \text{Pa}) (0.0573\text{m}^3) - (100 \cdot 10^3 \text{Pa}) (0.2\text{m}^3)) = -2.67\text{kJ}.$$

■

Remark 7.2. For a polyprotic process, we can use the above expression for work when the fluid is an ideal gas and $n \neq 1$. If n where unity, then $PV = C$ for a constant C . For an ideal gas, we can still find an expression for the work. If $PV = mRT$ is a constant, then the process must be isothermal, Thus, for an ideal gas undergoing an isothermal process,

$$W = \int_{V_1}^{V_2} P dV = mRT \int_{V_1}^{V_2} \frac{dV}{V} = mnRT \frac{V_2}{V_1},$$

where $n = 1$ in an ideal gas.

§7.2 Types of Processes

When the process is isobaric (constant P), $n = 0$. When the process is isothermic (constant T), then $n = 1$. Otherwise, when the process is adiabatic ($Q = 0$), then $n = 1 - \gamma$.

§8 July 28, 2017

§8.1 Property Table Examples

To determine which property table to use for a given problem, we first need to compare with the saturation conditions.

Example 8.1

Determine the number of phases that are present when water is at 1.5MPa and 600°C .

Solution. Consulting the *Table A-5, Saturated water - Pressure table*, the saturation temperature at 1500kPa is found to be 198.29°C . Thus, at 600°C , we have a temperature that is greater than the saturated temperature. Therefore, we have a superheated vapour. ■

Example 8.2

Determine the phases that are present when water is at 1.5MPa and 20°C .

Solution. Since we are below the saturation temperature at 1.5MPa , we have a compressed liquid. ■

Example 8.3

Determine the phases that are present when $P = 1.5\text{MPa}$ and quality $x = 0.6$.

Solution. Quality is only defined when we are in the two phase region. Thus, we have vapour and liquid. ■

Example 8.4

Determine the number and type of phases present at $P = 1.5\text{MPa}$ and $h = 2300\text{kJ/kg}$.

Solution. Consulting *Table A-5* for enthalpy, we note that the given value of h is between the h_f of the saturated liquid (844.55kJ/kg) and h_g of the saturated vapour (2791.0kJ/kg). Thus, we are again in the two phase region. Since $h_f < h < h_g$, we have a saturated liquid in equilibrium with a saturated vapour. We can calculate the quality,

$$x = \frac{h - h_f}{h_g - h_f} = \frac{2300 - 844.55}{2791 - 844.55} = 0.748.$$

■

Remark 8.5. To find quality, we can use specific volume, internal energy, enthalpy, or entropy values. In the above example, we used the enthalpy values h . If we want to find the enthalpy value below that of the saturated liquid h_f , we can determine the temperature from the pressure, then consult *Table A-4*. We can then linearly interpolate for the saturation temperature in order to determine h .

Example 8.6

A rigid tank contain 50kg of water at 90°C . If the water is known to be a saturated liquid, determine the volume that it occupied.

Solution. We will assume that the tank is completely full of water. Since we have a saturated liquid at a given temperature, we use *Table A-4*. The volume is therefore the specific volume multiplied by the mass, so

$$V = v \cdot m = (0.001036\text{m}^3/\text{kg}) (50\text{kg}) = 0.0518\text{m}^3.$$

The pressure of 70.183kPa (saturation pressure) in the tank can be determined by consulting *Table A-4* for water at 90°C . ■

Example 8.7

Determine the volume that water occupied when $P = 4\text{MPa}$, $T = 420^\circ\text{C}$, and $m = 2\text{kg}$.

Solution. Consulting *Table A-5* at the specified pressure, we note that our temperature is greater than the saturation temperature. Thus, we have superheated water. We can then perform a linear interpolation on the entries of *Table A-6* to find the specific volume of the superheated water. Then, we can use the given mass to find the total volume. ■

Example 8.8

Determine the specific volume of water at 0.18MPa and 170°C .

Solution. Consulting *Table A-4*, since the pressure is less than the saturation pressure, we are in the superheated vapour region. We now consult *Table A-6*. We have tables at $P = 0.1\text{MPa}$ and $P = 0.2\text{MPa}$. We will now linearly interpolate between these two tables between $T = 150^\circ\text{C}$ and $T = 200^\circ\text{C}$ to find the specific volume v at 170°C at these two pressures. We then interpolate for our pressure of 0.18MPa . ■

Chapter 1, 2, part of 4 <http://www.sfu.ca/~mbahrami/ENSC%20388/>