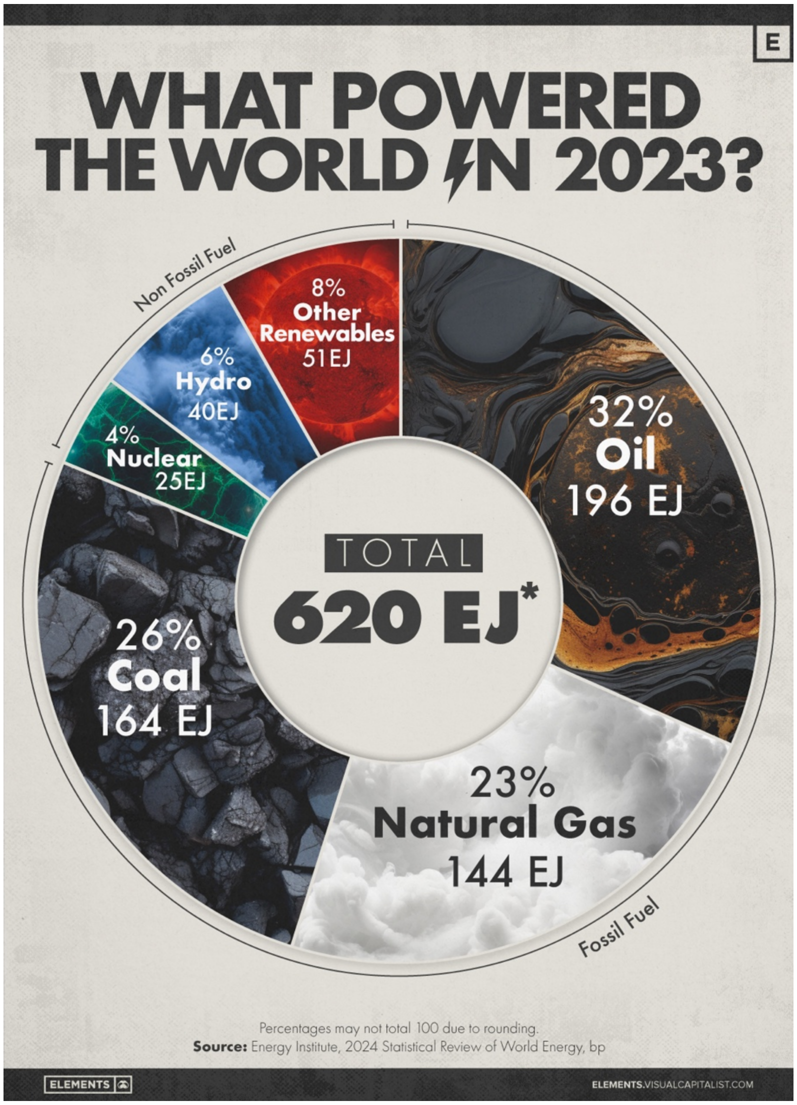
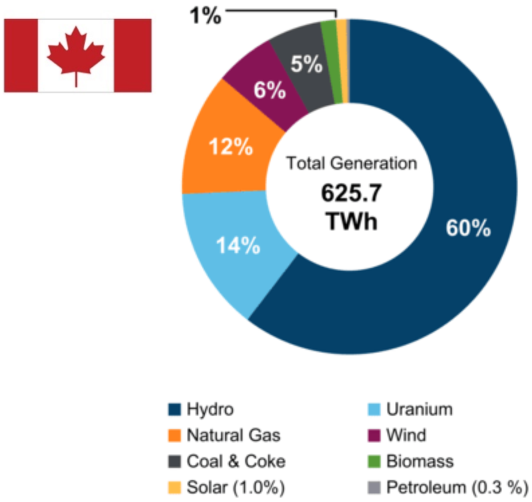
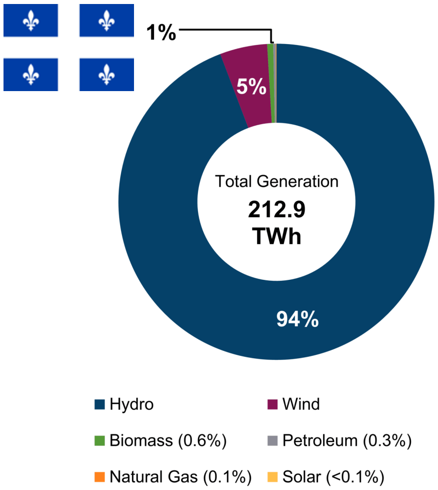
MECH 451 – Course Notes – v. pre-α

Renewable Energy Fundamentals and Applications (MECH 451)

Course Notes


WHAT POWERED THE WORLD IN 2023?
Non Fossil Fuel
8% Other Renewables 51EJ
6% Hydro 40EJ
4% Nuclear 25EJ
32% Oil 196 EJ
TOTAL 620 EJ*
26% Coal 164 EJ
23% Natural Gas 144 EJ
Fossil Fuel
Percentages may not total 100 due to rounding.
Source: Energy Institute, 2024 Statistical Review of World Energy, bp
ELEMENTS
ELEMENTS.VISUALCAPITALIST.COM

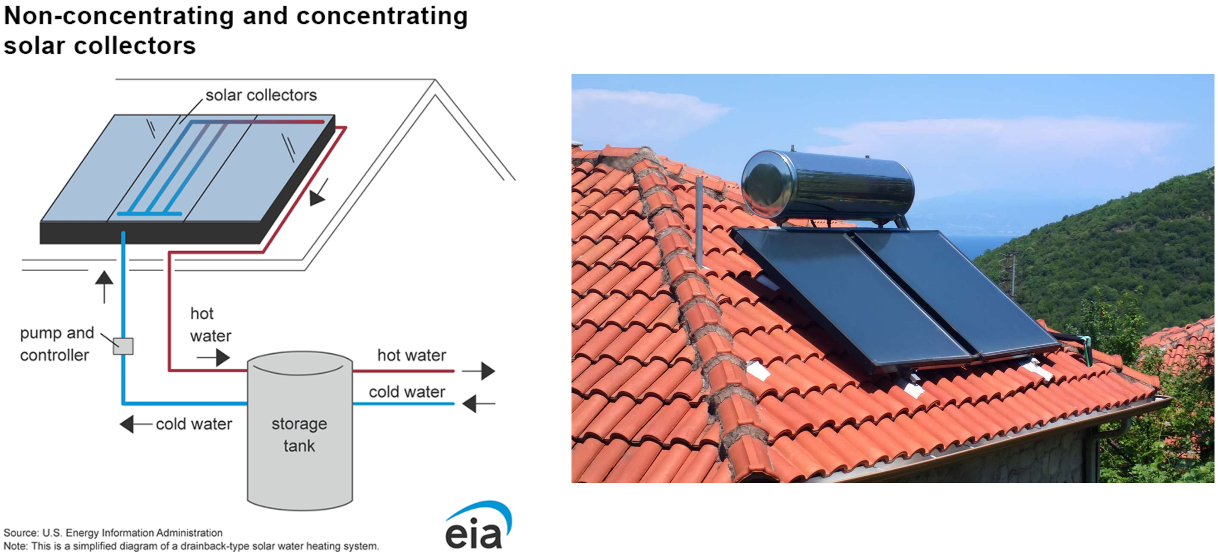

1%
5%
6%
12%
14%
60%
Total Generation
625.7 TWh
Hydro
Uranium
Natural Gas
Wind
Coal & Coke
Biomass
Solar (1.0%)
Petroleum (0.3 %)


1%
5%
94%
Total Generation
212.9 TWh
Hydro
Wind
Biomass (0.6%)
Petroleum (0.3%)
Natural Gas (0.1%)
Solar (<0.1%)

CHAPTER 1

Review of Thermal Sciences

A deep understanding of renewable energy processes and fundamental terms is essential for students in mechanical and aerospace engineering. More specifically, for the context of this course, thermodynamics (ENGR251 and MECH351), heat transfer (MECH352), and fluid mechanics (ENGR361 and MECH361) are crucial. This is because several renewable energy systems' fundamentals and design requirements necessitate a combination of analyses based on multiple thermal fluid sciences. For instance, consider the solar collector shown below [Figure 1.1]. Its design requires the application of thermodynamics to determine the amount of energy transfer, heat transfer to calculate the size of the heat exchanger, and fluid mechanics to select the appropriate size and type of pump.



Non-concentrating and concentrating solar collectors

Source: U.S. Energy Information Administration
Note: This is a simplified diagram of a drainback-type solar water heating system.

Figure 1.1. Solar collectors

1.1. REVIEW OF THERMODYNAMICS

Thermodynamics is the science of energy, often referred to as the science of entropy. The most critical fundamental knowledge required for the analysis of renewable energy systems is the first law of thermodynamics, which dictates that energy is conserved. The first law of thermodynamics is a conservation law, meaning that energy cannot be created or destroyed; it can only be transformed from one form to another (e.g., kinetic to potential, kinetic to heat, heat to work, etc.). The figure below illustrates the principle of conservation of energy.

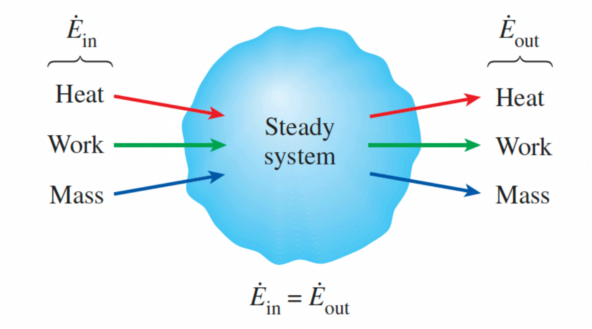


Figure 1.2. Conservation of energy

Thus, the total energy in our universe has remained constant in the past and, according to the current state of knowledge in physics, is expected to remain the same in the future.

Simply stated the conservation of energy can be written as:

$$\begin{pmatrix} Total\ energy \\ entering\ the\ system \end{pmatrix} - \begin{pmatrix} Total\ energy \\ leaving\ the\ system \end{pmatrix} = \begin{pmatrix} Change\ in\ the\ total \\ energy\ of\ the\ system \end{pmatrix}$$

$$E_{in} - E_{out} = \Delta E_{system}$$

The first law of thermodynamics simply illustrates the conservation of energy. It can lead to processes that we don't experience in our universe since it does not put any restrictions on the direction of the process. This is the role of the Second Law. The Second Law of Thermodynamics has different statements but simply stated, it asserts that energy has not only a quantity but also a quality, and that actual processes occur in the direction of a decrease in the quality of energy.

1.1.1 Heat and other forms of energy

Energy can take different forms at the macroscopic level (thermal, mechanical, potential, electrical, magnetic, chemical, or nuclear) or the microscopic level (energy associated with the molecular structure of the system and the degree of molecular activity). The sum of all macroscopic forms of energy is called the internal energy of the system (U). Internal energy can also be viewed as the sum of the kinetic and potential energy of the molecules.

The internal energy associated with the kinetic energy of the molecules is called **sensible energy** or sensible heat. Note that the kinetic energy of a gas is proportional to its temperature, and for a monoatomic ideal gas:

$$U = \frac{3}{2} nRT$$

The internal energy is associated with intermolecular forces between the molecules of the system. Such intermolecular forces are stronger if the system is in the solid phase than in the liquid or gas phases. If sufficient energy is provided to the system to overcome the intermolecular forces, a phase change will occur. The internal energy associated with the phase change is called **latent heat**.

The internal energy is also associated with the atomic bonds in a molecule. This energy is called **chemical energy**, whereas the internal energy associated with the bonds between the nucleus of the atoms themselves is called **nuclear energy**. The chemical energy is released during a chemical reaction, while the nuclear energy is released during a nuclear reaction.

Chemical Energy	internal energy associated with the atomic bonds.
Nuclear energy	internal energy associated to it the nucleus of the atom itself

Internal energy can be viewed as the summation of the kinetic energy and potential energy of the molecules

Unit of energy: The international unit of energy is Joule [J] or kilo joules following press crown jewel the British scientist who performed the experiment that clearly showed the equivalence between heat and work. The major contribution of Mayer should however not be disregarded. in the English system the unit of energy is the British thermal system or [BTU] define at the energy required to raise the temperature of 1lbm of water at 60° F by 1° F. Note that the magnitude of kilo joules and BTU are almost identical wed 1 BTU is equal 1.055056 J. another unit of energy frequently used, for example in food industry, is the calorie with 1 cal = 4.1868 J. The Cal is defined as the energy required to raise the temperature of 1g of water at 14.5° C by 1° C.

Internal Energy = (Kinetic Energy) + (Potential Energy)

The part associated with kinetic energy is also called **sensitive energy** or sensitive heat. The kinetic energy of molecules is proportional to the temperature.

$$\Uparrow T \rightarrow \Uparrow \Delta E_K \rightarrow \Uparrow \Delta U$$

1.1.2. Saturation temperature and saturation pressure

$\mathbf{T_{sat}}$	*temperature at which a pure substance changes phase at a certain pressure*
$\mathbf{P_{sat}}$	*pressure at which a pure substance changes phase at a certain temperature*

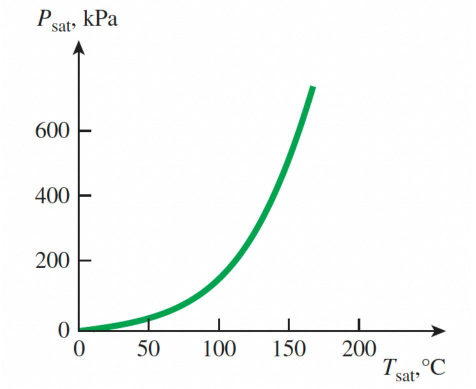


Figure 1.3. Variation of the saturation pressure (P_{sat}) as a function of the saturation temperature (T_{sat}) for water

1.1.3. Specific heats of gases, liquids and solids

Specific heat is the energy required to raise the temperature of the unit of mass of a substance by 1°. We are usually interested in the specific heat at constant volume [C_V] and at constant pressure [C_P], with Cp > Cv and Cp – Cv = R.

The specific heat of the substance usually depends on temperature and pressure. But in the case of an ideal gas the specific heat is only a function of temperature.

Reminder: Ideal gas → ($P_R << 1$) or ($P_R < 10$ & $T_R > 2$)

with P_R : reduced pressure and T_R : reduced temperature

For an ideal gas, we can write:

$$du = c_v dT \qquad \text{and} \qquad dh = c_p dT$$

And

$$\Delta u = c_{v,\text{avg}} \Delta T \qquad \text{and} \qquad \Delta h = c_{p,\text{avg}} \Delta T \qquad \text{(kJ/kg)}$$

If we want this in kJ instead of kJ/kg, we need to multiply by the mass:

$$\Delta U = mc_{v,\text{avg}} \Delta T \qquad \text{and} \qquad \Delta H = mc_{p,\text{avg}} \Delta T \qquad \text{(kJ)}$$

Specific heats (C_P and C_V) are constant for incompressible substances, where the specific volume (*v*) does not change significantly with temperature (T) or pressure (P). In such cases, we can omit the subscripts on C_P and C_V, leaving just C. Thus, for liquids and solids, the following relationship applies:

$$\Delta U = mc_{\text{avg}} \Delta T \qquad \text{(kJ)}$$

1.1.4. Energy transfer

In classical thermodynamics, energy can be transferred by heat and/or work.

Heat (q or Q)	Due to difference in temperature. $Q = m\,q$ and $\dot{Q} = \frac{Q}{\Delta t}$ (more specifically: $Q = \int_0^{\Delta t} \dot{Q}\, dt$ and for $\dot{Q} = Cte$ Then $Q = \dot{Q}\Delta t$
Work (w or W)	Due to motion (electric work, shaft work, spring work, piston work) $W = m\,w$ and $\dot{W} = \frac{W}{\Delta t}$

1.1.5. The first law of thermodynamics

For a closed system

$$\frac{dE_{system}}{dt} = \dot{Q} - \dot{W}$$

For an open system

Conservation of mass:

$$\frac{dm_{CV}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

with the mass flow rate: $\dot{m} = \rho V A$ *and the volumetric flow rate:* $\dot{V} = VA = \frac{\dot{m}}{\rho}$

Conservation of energy:

$$\frac{dE_{CV}}{dt} = \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

Example 1.1

You are managing a small office and decide to install an electric heating system to ensure the space is comfortable during the winter months. The system consists of a 250-W fan, which circulates the air, and an electric resistance heating element that heats the air as it flows through the ducts. The ventilation system is designed to push air at a steady flow rate of 0.5 kg/s through the ductwork, and the temperature of the air rises by 7°C as it passes through the heater. However, you also know that some heat is lost to the surroundings due to imperfect insulation in the ducts, and it is estimated that around 400 W of heat is lost to the environment.

You want to calculate the power rating of the electric heating element required to ensure the air reaches the desired temperature, considering the energy lost in the system.

1.2. Review of heat transfer

By definition, heat is the energy transferred due to a difference or, more specifically, a gradient in temperature. Heat transfer is the science that focuses on determining the rates at which energy is transferred in the form of heat.

$$\boldsymbol{Heat\ Transfer} \begin{cases} Conduction \\ Convection \\ Radiation \end{cases}$$

Heat is always transferred from high temperature to low temperature body or system.

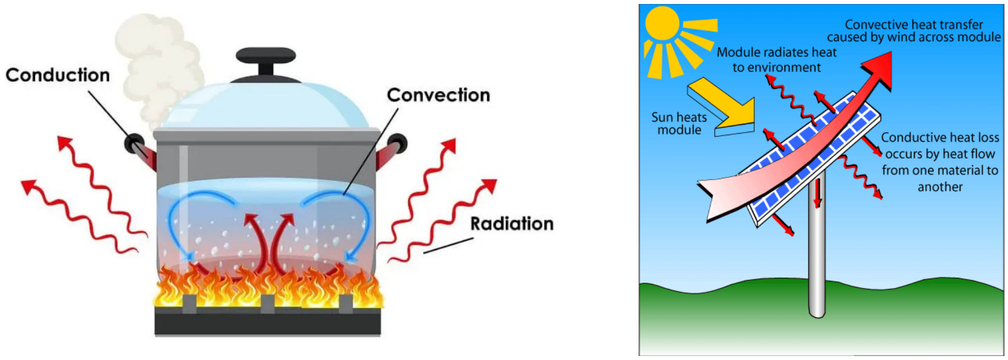


Figure 1.4. Modes of heat transfer

1.2.1 Conduction

Conduction is the form of heat transfer that occurs between more energetic particles in solids, liquids, or gases and less energetic adjacent particles. The energy is transferred through collisions and diffusion.

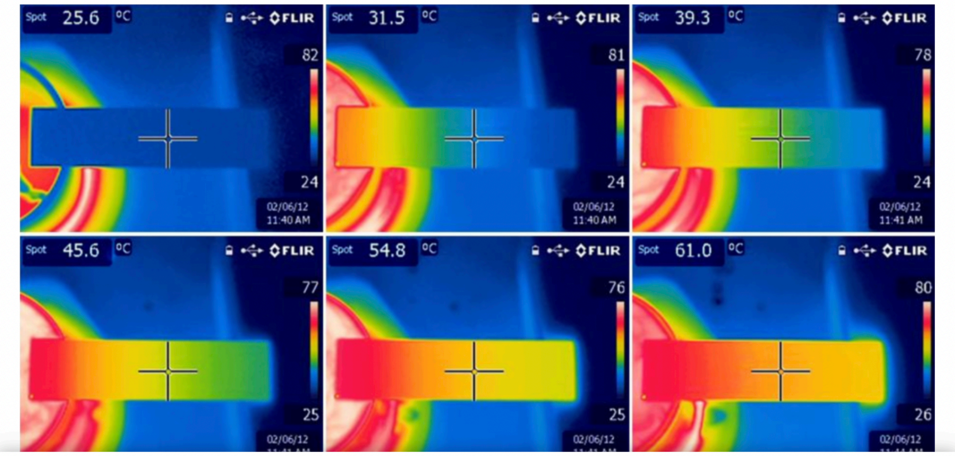
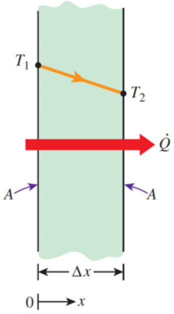


Figure 1.5. Series of screenshots taken from an IR video capturing conduction through an aluminum bar in real-time

The rate of heat transfer depends on the geometry of the medium, its thickness, the properties of the medium, and the temperature difference. The heat transferred by conduction is governed by Fourier's Law for steady-state conduction:

$$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx} \qquad \text{(kW)}$$



$\frac{dT}{dx}$ represents the temperature gradient (or the slope of the temperature curve on a T-x diagram)

The negative sign in Fourier's Law ensures that the rate of heat transfer is positive in the direction of decreasing temperature. (k) is the thermal conductivity, which represents the ability of the medium to conduct heat. A higher value indicates that the medium conducts heat more efficiently. We can also think of it in the reverse way: a medium with a lower thermal conductivity act as a much better insulator. Note: k should not be confused with C_P and C_V, which are indicators of the medium's ability to store thermal energy, not to conduct it.

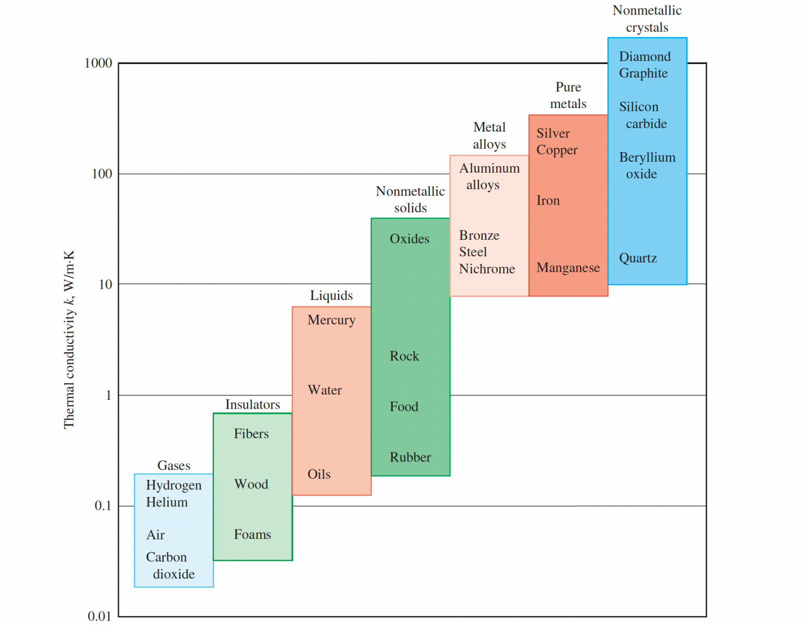


Figure 1.6. Thermal conductivity for various materials at room temperature

From the kinetic theory of gases, one can predict that $k = f(\sqrt{T}, \frac{1}{M})$, so $k = f(T)$, so k is a function of temperature. The value of k for liquids is smaller than for solids but higher than for gases, and it is generally not a function of pressure (except near the critical point). For liquids, the value of k typically decreases with an increase in temperature, with water serving as an example. In solids, heat conduction occurs due to lattice vibrational waves and the free flow of electrons.

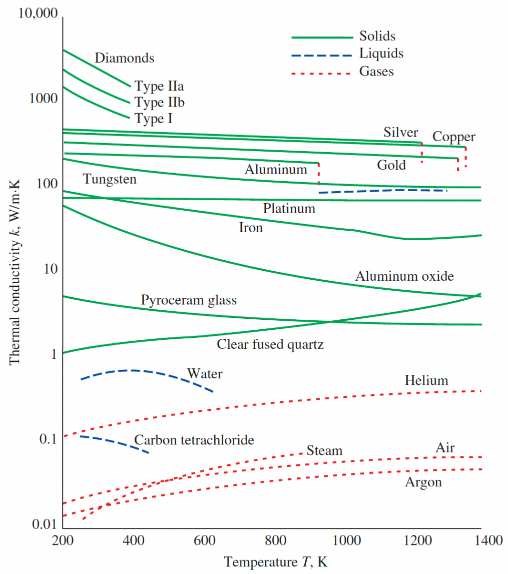


Figure 1.6. Variation of the thermal conductivity of various solids, liquids, and gases with temperature

The value of k for certain metals can reach extremely high values at very low temperatures, near absolute zero. This is because some materials exhibit superconductivity at such low temperatures. For several applications, we often assume the thermal conductivity to be constant at the average temperature.

Example: $k_{Cooper}^{T=293K} = 401 \frac{W}{mK}$ while $k_{Cooper}^{T=20K} = 20{,}000 \frac{W}{mK}$

1.2.2. Convective heat transfer

Convection is, by definition, the mode of heat transfer that involves fluid motion. It typically occurs between a solid surface and an adjacent liquid or gas. The faster the fluid motion, the greater the energy transfer through convection. If the fluid (liquid or gas) is stationary and has a uniform temperature at the surface, the primary mode of heat transfer is conduction. Fluid motion enhances heat transfer but also makes the process more complex from a fundamental perspective.

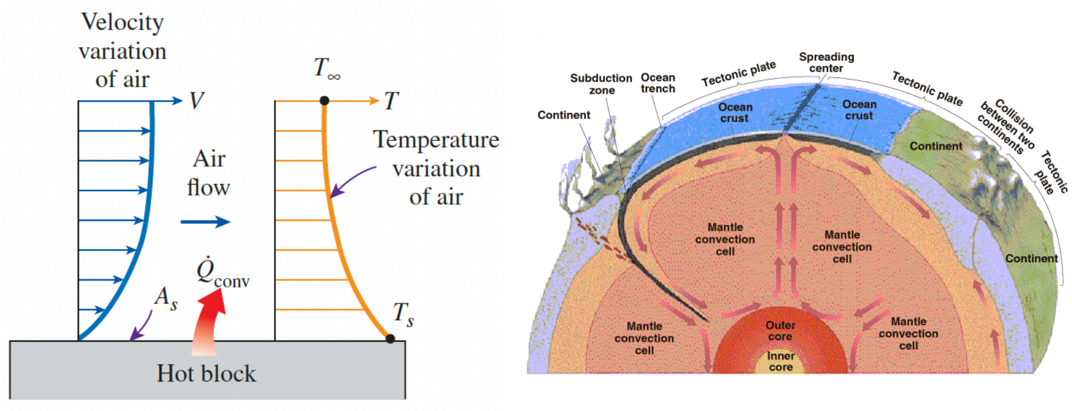


Figure 1.7. Heat transfer by convection

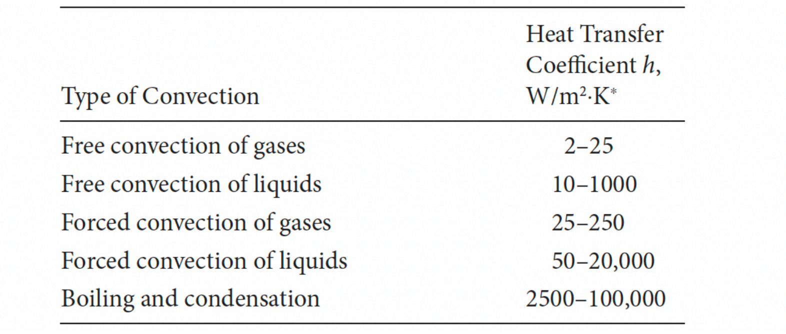
There are two modes of convection:

1. **Natural or free convection**: This occurs when the fluid motion is not externally forced but is driven by buoyancy forces caused by density differences due to temperature variations.
2. **Forced convection**: This occurs when the fluid is 'forced' to flow by an external source, such as a fan, pump, or wind.

The rate of convective heat transfer is proportional to the temperature difference and is evaluated using Newton's Law of Cooling:

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty)$$

Where h is the heat transfer coefficient (W/m^2 K), A_s is the surface area, T_S is the surface temperature and T_∞ is the temperature of a fluid far enough from the surface.



Type of Convection	Heat Transfer Coefficient h, W/m²·K*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

Note that the convection heat transfer coefficient is not a property of the fluid; rather, it depends on several factors such as the surface geometry, the properties of the fluid, and the velocity of the fluid. It is typically determined experimentally.

1.2.3. Radiation heat transfer

Radiation is a mode of energy transfer emitted by matter in the form of electromagnetic waves. It arises due to changes in the electronic configuration of atoms and does not require the presence of a medium. For example, consider the energy from the sun that reaches the Earth through space.

There are several forms of electromagnetic radiation, including microwaves, radio waves, and X-rays. In this course, we mainly focus on one type of radiation: **thermal radiation**, which occurs due to the temperature difference between bodies. All bodies above absolute zero emit thermal radiation.

Although radiation is fundamentally an electromagnetic phenomenon, for solids, we typically consider only the effect of the surface. The radiation emitted by the core of a solid is negligible or ignored, as it is generally unable to reach the surface.

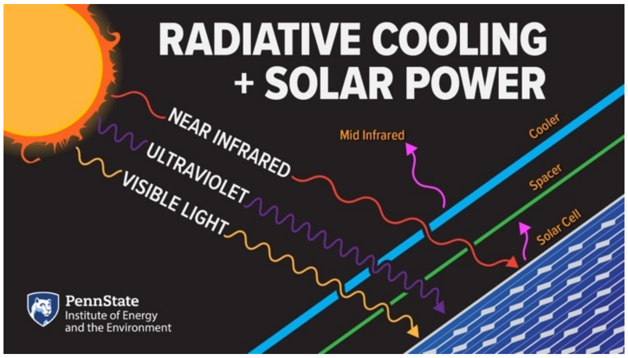


Figure 1.8. Radiative cooling of solar cells

The maximum rate of radiation that can be emitted by a surface at temperature T is:

$$\dot{Q}_{\text{emit,max}} = \sigma A_s T_s^4$$

This situation is called Stefan-Boltzmann Law.

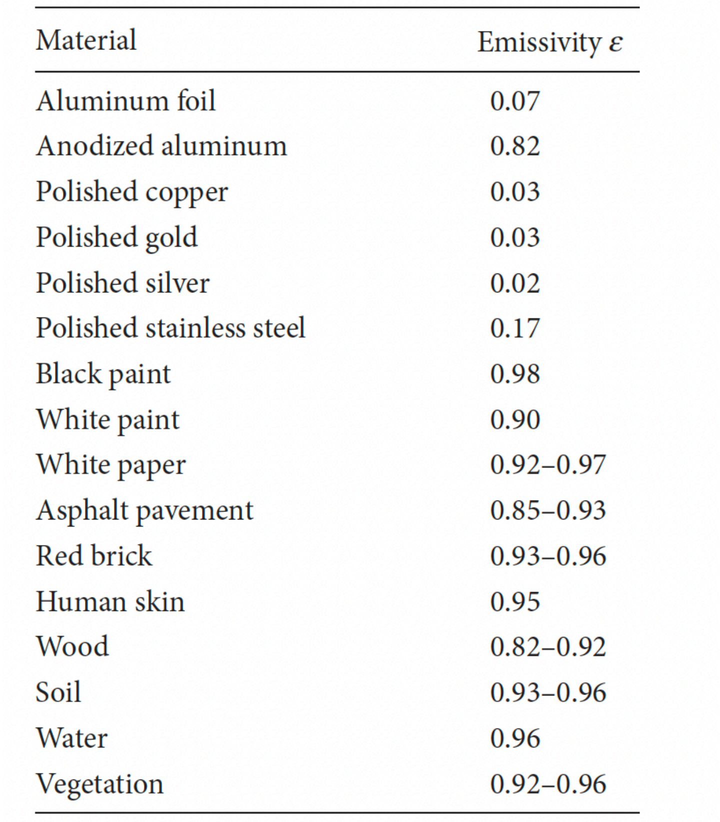
Where σ is the Stefan-Boltzmann constant: $\sigma = 5.670\ 10^{-8}$ W/(m^2 K^4)

If a body is capable of emitting radiation at this maximum value, it is called a black body, and the radiation emitted is referred to as black body radiation. However, in real life, most bodies do not emit radiation at this maximum rate but at a lower rate. To account for this, a coefficient ε, called the emissivity of the surface, is introduced. The value of ε ranges between 0 and 1, with ε = 1 representing a black body.

Thus, the Stefan-Boltzmann law becomes:

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4$$

The table below provides values of ε for some materials at 300 K.



Material	Emissivity ε
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

Absorptivity (α) represents the fraction of the radiation energy incident on a surface that is absorbed. The value of α ranges between 0 and 1, with α = 1 for a black body. This implies that a black body is both a perfect emitter (ε = 1) and a perfect absorber (α = 1).
We can write:

$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}}$$

And

$$\dot{Q}_{\text{net}} = \dot{Q}_{\text{emit}} - \dot{Q}_{\text{absorbed}}$$

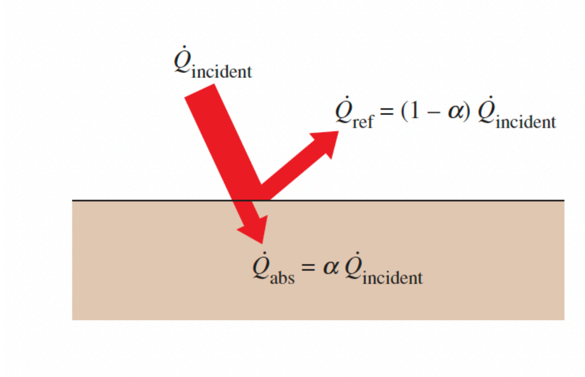


Figure 1.9. The absorption of radiation incident on an opaque surface of absorptivity α. (abs: absorbed; ref: reflected)

Now if we consider two surfaces, we can write:

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s(T_s^4 - T_{\text{surr}}^4)$$

This is an idealized approach since the radiation between two bodies is significantly influenced by several parameters, such as the medium and the orientation of the bodies. Here, we assume that the surroundings completely enclose the body, with the surface and the medium in between do not interfere in the radiation process.

In practical applications, it is rare to encounter a single mode of heat transfer. Therefore, we account for the different modes of heat transfer by defining a combined heat transfer coefficient that includes both convection and radiation.

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = h_{\text{conv}}A_s(T_s - T_\infty) + \varepsilon\sigma A_s(T_s^4 - T_{\text{surr}}^4)$$
$$\dot{Q}_{\text{total}} = h_{\text{combined}}A_s(T_s - T_\infty)$$
$$h_{\text{combined}} = h_{\text{conv}} + h_{\text{rad}} = h_{\text{conv}} + \varepsilon\sigma(T_s + T_{\text{surr}})(T_s^2 + T_{\text{surr}}^2)$$

Note that: $(\dot{Q}_{Conduction};\ \dot{Q}_{Natural\ convection}) < \dot{Q}_{Radiation} \ll \dot{Q}_{Forced\ convection}$

So typically, $\dot{Q}_{Radiation}$ is neglected compared to $\dot{Q}_{Forced\ convection}$ if ε << and the temperature is low to moderate.

Example 1.2

A thermal management system is being developed for a high-performance industrial heat exchanger used in a mechanical engineering application. The system consists of two large parallel metal plates maintained at constant temperatures of T_1 = 320 K and T_2 = 276 K, separated by a uniform gap of L = 3 cm. The surfaces of the plates are highly polished to behave as black bodies (ε = 1).

Analyze the rate of heat transfer per unit surface area between the plates under the following conditions:

(a) The gap between the plates is filled with atmospheric air (k_air = 0.02551 W/m·K).
(b) The gap is evacuated, allowing only radiation heat transfer.
(c) The gap is filled with fiberglass insulation (k_ins = 0.036 W/m·K).
(d) The gap is filled with superinsulation material with an apparent thermal conductivity of k_super = 0.00015 W/m·K.

Determine the heat transfer rates in each case and assess their implications for optimizing the thermal performance of the heat exchanger.

1.3. Review of fluid mechanics

Fluid mechanics is the science that deals with the behavior of fluids at rest or in motion. It is primarily divided into the study of incompressible fluids and compressible fluids (gas dynamics).

The viscosity of a fluid generates a force that opposes motion. Viscosity is a characteristic property of a fluid and measures its resistance to deformation.

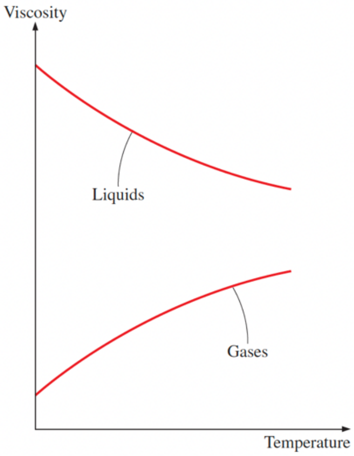
For Newtonian fluids, where the rate of deformation is linearly proportional to the shear stress, and for one-dimensional shear flow, we can write:

$$\tau = \mu \frac{du}{dy}$$

τ	shear stress
μ	coefficient of viscosity or dynamic viscosity

The dynamic viscosity is a function of the temperature, but the behavior is different for liquid and gases.

For liquids	$\mu \sim f(\frac{1}{T})$	Because temperature increases the energy that overcomes intermolecular forces, and the fluid can move more freely.
For gases	$\mu \sim f(T)$	Intermolecular forces are negligeable. A higher temperature increases the number of collisions and leads to a greater resistance to flow.



1.3.1. Pressure drop in fluid flow in pipes

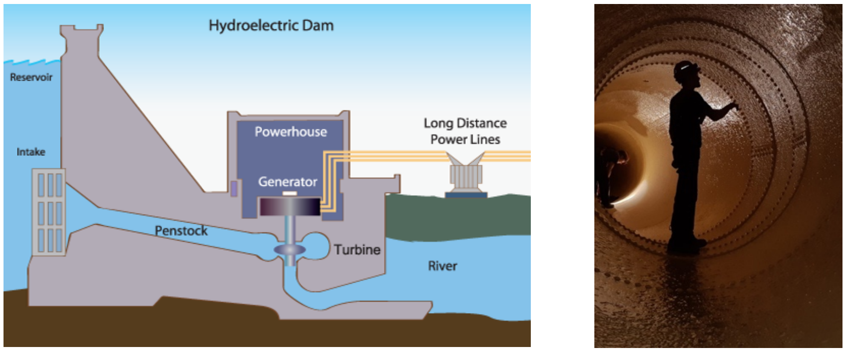


Figure 1.10. Hydroelectric dam and inside of the penstock. The evaluation of the pressure drop in the penstock is important to determine the power produced.

The pressure loss, or head loss, for laminar or turbulent flow in a pipe (circular or non-circular) with smooth or rough surfaces can be expressed as:

$$\Delta P_L = f \frac{L}{D} \frac{\rho V^2}{2}$$

L	length of the pipe
D	characteristic dimension of the cross section
$\frac{\rho V^2}{2}$	dynamic pressure
f	friction coefficient

this can also be expressed as a head loss:

$$h_L = \frac{\Delta P_L}{\rho g} = f \frac{L}{D} \frac{V^2}{2g}$$

<u>For a laminar flow in round pipes</u>: $f = \frac{64}{Re}$

The pressure drop for laminar flow in a horizontal pipe can be written following the Hagen-Poiseuille law as:

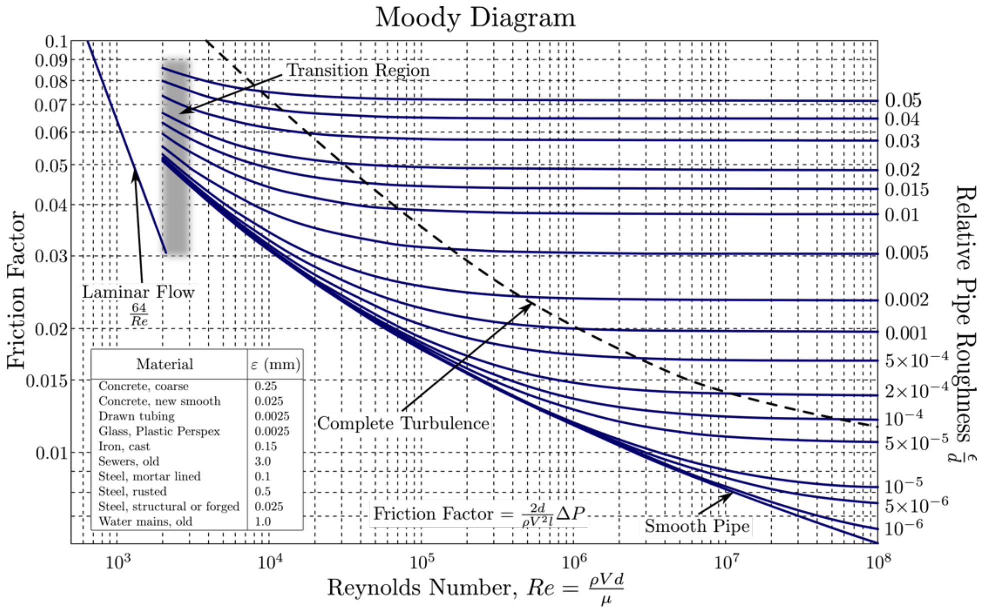
$$\Delta P = \frac{32 \mu L V_{\text{avg}}}{D^2}$$

For non-circle pipes the diameter is replaced by the hydraulic diameter $\left(D_h = \frac{4A_c}{P}\right)$, where A_c is the cross-sectional area and P is the wetted perimeter.

<u>In fully turbulent flows</u>, f is a function of the Re and the relative roughness ε/D. The friction coefficient (f) can be obtained then using the Colebrook equation:

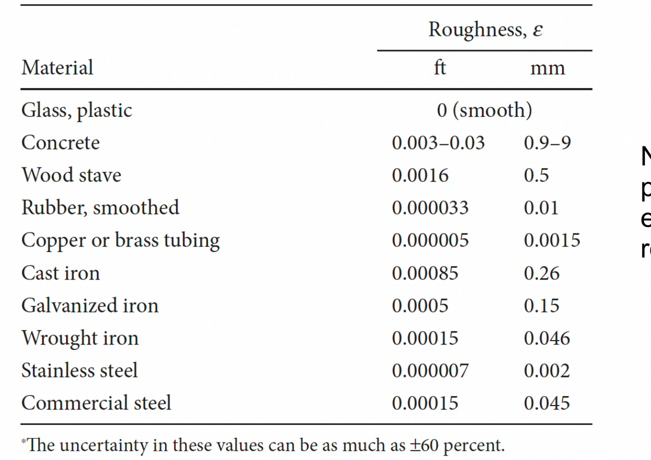
$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\varepsilon / D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}} \right)$$

The graphical representation of this formula is known as the Moody chart.



Material	ε (mm)
Concrete, coarse	0.25
Concrete, new smooth	0.025
Drawn tubing	0.0025
Glass, Plastic Perspex	0.0025
Iron, cast	0.15
Sewers, old	3.0
Steel, mortar lined	0.1
Steel, rusted	0.5
Steel, structural or forged	0.025
Water mains, old	1.0

Below is a table reporting various values for new commercial pipe roughness.



Material	Roughness, ε ft	mm
Glass, plastic	0 (smooth)	
Concrete	0.003–0.03	0.9–9
Wood stave	0.0016	0.5
Rubber, smoothed	0.000033	0.01
Copper or brass tubing	0.000005	0.0015
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Wrought iron	0.00015	0.046
Stainless steel	0.000007	0.002
Commercial steel	0.00015	0.045

*The uncertainty in these values can be as much as ±60 percent.

Note that for a given pipe, the roughness is provided for new pipes, while aging pipes can experience a significant increase in effective roughness, with factors ranging from 5 to 10.

As you can see, we have two different equations: one valid for laminar flow, and the second valid only for fully developed turbulent flow. An alternative approach is to use the Churchill equation, which is valid for any Reynolds number, any roughness, and even for regimes transitioning from laminar to turbulent flow:

$$f = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + (A+B)^{-1.5}\right]^{\frac{1}{12}}$$

With

$$A = \left\{-2.457 \cdot \ln\left[\left(\frac{7}{\mathrm{Re}}\right)^{0.9} + 0.27\frac{\varepsilon}{D}\right]\right\}^{16}$$

Once the pressure loss in the pipe is known, the required pumping power to overcome these losses can be calculated.

$$\dot{W}_{\mathrm{pump},L} = \dot{V}\Delta P_L = \dot{V}\rho g h_L = \dot{m} g h_L$$

With $\dot{V}$ is the volume flow rate and $\dot{m}$ is the mass flow rate.

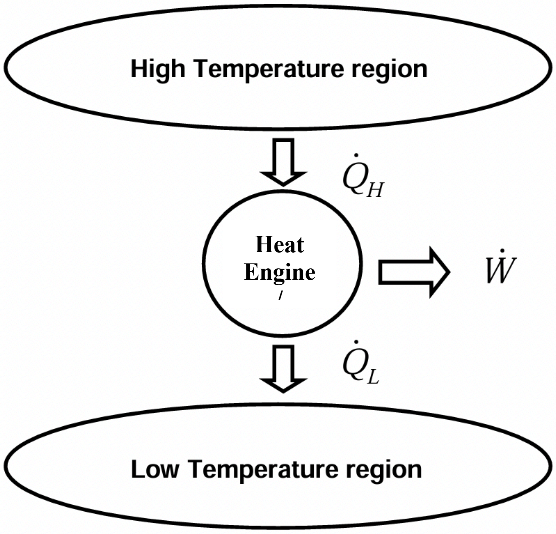
Example 1.3

In a solar water heating system, water is circulated through a long horizontal stainless-steel pipe to transfer heat from the solar collector to a storage tank. The pipe has a length of L = 30 m and an internal diameter of D = 5 cm. Water enters the pipe at T = 15°C with properties ρ = 999.1 kg/m³ and μ = 1.138 × 10⁻³ kg/m·s, and it flows steadily at a rate of Q = 9 L/s.

Determine the pressure drop, the head loss, and the pumping power required to circulate the water through the pipe, assuming steady-state conditions.

1.4. Review of thermodynamic cycles

1.4.1. Heat engines



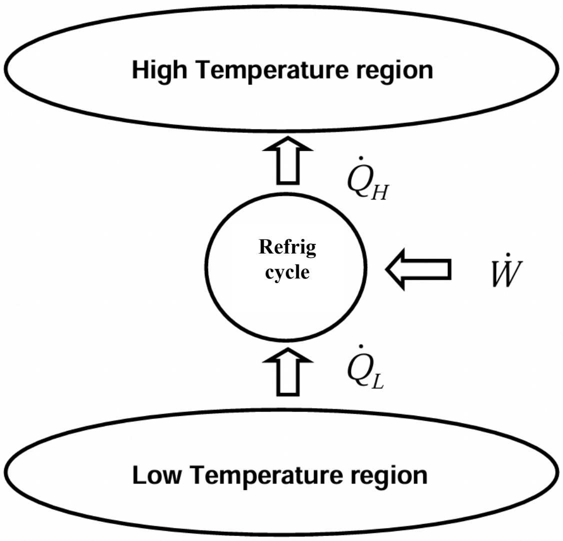
From the first law of thermodynamics:

$$\dot{Q}_H = \dot{Q}_L + \dot{W}$$

For a Carnot heat engine (max efficiency):

$$\eta = 1 - \frac{T_L}{T_H}$$

1.4.2. Refrigeration cycle



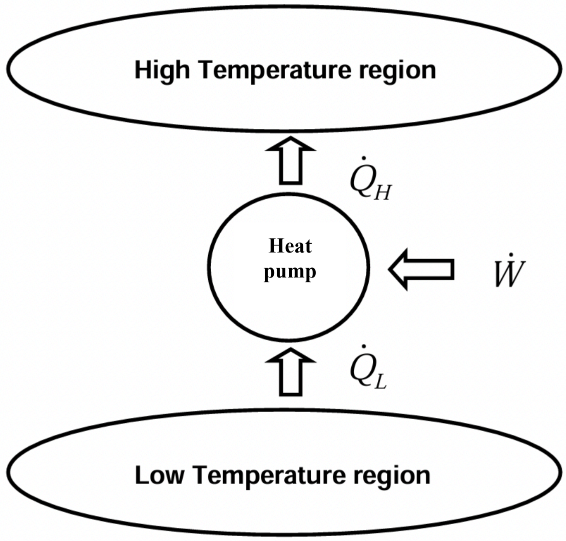
From the first law of thermodynamics:

$$\dot{Q}_H = \dot{Q}_L + \dot{W}$$

For a Carnot refrigeration cycle (max efficiency):

$$COP = \frac{1}{\frac{T_H}{T_L} - 1}$$

1.4.3. Heat pumps



From the first law of thermodynamics:

$$\dot{Q}_H = \dot{Q}_L + \dot{W}$$

For a Carnot heat pump (max efficiency):

$$COP = \frac{1}{1 - \frac{T_L}{T_H}}$$

1.5. Review of chemical reactions and combustion

In a process involving combustion, new components are created while others are destroyed. Therefore, it is important to consider the energy required to create or destroy these components. Let us consider a simple example: the combustion of propane (C_3H_8) in a pure oxygen environment:

$$\mathbf{C_3H_8 + 5\,O_2 \rightarrow 3\,CO_2 + 4\,H_2O}$$

To balance this reaction, the number of atoms of each element must remain the same before, after, and during the chemical reaction. Note that during a chemical reaction, there is conservation of mass and the number of atoms, but not conservation of the total number of moles (for the combustion of propane: 6 moles on the left side compared to 7 moles on the right side).

Here, we will first consider complete combustion, i.e., the products of the combustion of a hydrocarbon fuel will be H_2O and CO_2.
Incomplete combustion, on the other hand, will result in products that contain H_2, CO, C, or OH. The causes of incomplete combustion are usually insufficient oxygen or poor mixing.

For the above example, we hypothesized combustion in a pure oxygen environment, which is obviously not the case in practice. In reality, air is used for combustion. Here, we will assume that air consists of 21% O_2 and 79% N_2 by volume. Therefore, for each mole of O_2 involved in the reaction, we will have:

$$\frac{79}{21} = 3.76 \frac{mol\ N_2}{mol\ O_2}$$

For air, we will have: 1 kmol O_2 + 3.76 kmol N_2 = 4.76 kmol of air.

However, since N_2 will not undergo any chemical reaction, the combustion of propane with air can be written in the following form:

$$C_3H_8 + 5\,(O_2 + 3.76\,N_2) \rightarrow 3\,CO_2 + 4\,H_2O + 18.8\,N_2$$

When analyzing a chemical reaction, the components that exist before the reaction are called reactants (C_3H_8, O_2, and N_2), and the components that exist after the reaction are called products (CO_2, H_2O, and N_2).

Complete combustion of a hydrocarbon does not occur with any amount of air. In fact, a minimum amount of air that supplies O_2 is required. This amount of air is called theoretical air. In practice, however, the amount of air used is higher than the theoretical air. This is done to increase the chances of complete combustion or to control the temperature of the combustion chamber. When we say 50% excess air, we mean that we are using 100% + 50% = 150% of the theoretical air.

1.5.1. Air-Fuel ratio (AF)

The parameter that relates the amount of air used and the fuel in a combustion process is the air-fuel ratio (AF):

$$AF = \frac{mass\ of\ air}{mass\ of\ fuel} = \frac{m_a}{m_f}$$

As an example, for the above reaction, the AF for theoretical air is:

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{5(4.76)(29)}{1(44)} = 15.69\,\frac{kg\ air}{kg\ fuel}$$

If we use an AF higher than 15.69, we are using a lean mixture. And if AF is less than 15.69, we are using a rich mixture.

1.5.2. Applying the first law to combustion processes

Before applying the first law to a combustion process, it is convenient to write the enthalpy of a component in a form suitable for use for reacting systems:

$$Enthalpy = \underbrace{\bar{h}_f^0}_{formation} + \left(\underbrace{\bar{h}}_{actual} - \underbrace{\bar{h}^0}_{reference} \right)$$

the first law can be written for an open system as:

$$Q_{in} + W_{in} + \underbrace{\sum N_r \left(\bar{h}_f^0 + \left(\bar{h} - \bar{h}^0\right)\right)_r}_{H_r} = Q_{out} + W_{out} + \underbrace{\sum N_p \left(\bar{h}_f^0 + \left(\bar{h} - \bar{h}^0\right)\right)_p}_{H_p}$$

N_r and N_P are the number of moles of the reactant or the product per mole of fuel.

And, the first law can be written for a closed system as:

$$Q_{in} + W_{in} + \underbrace{\sum N_r \left(\overline{h}_f^0 + \left(\overline{h} - \overline{h}^0 - P\overline{v}\right)\right)_r}_{H_r} = Q_{out} + W_{out} + \underbrace{\sum N_p \left(\overline{h}_f^0 + \left(\overline{h} - \overline{h}^0 - P\overline{v}\right)\right)_p}_{H_p}$$

Where the internal energy is expressed as a function of enthalpy (u = h - Pv), pressure, and specific volume. The choice of this form (using enthalpy rather than internal energy) is justified by the fact that enthalpy is tabulated.