CHAPTER 2: ENERGY AND THE FIRST LAW OF THERMODYNAMICS

Objectives:

- In this chapter we discuss energy and develop equations for applying the principle of conservation of energy.

Learning Outcomes:

- Demonstrate understanding of key concepts related to energy and the first law of thermodynamics. . . including internal, kinetic, and potential energy, work and power, heat transfer and heat transfer modes, heat transfer rate, power cycle, refrigeration cycle, and heat pump cycle.

- Apply closed system energy balances, observe sign convention for work and heat transfer.

- Conduct energy analyses of systems undergoing thermodynamic cycles, evaluating thermal efficiencies of **power cycles** and coefficients of performance of **refrigeration and heat pump cycles.**

Energy:

- Energy is a property of a system or object.
- Energy is defined as the capacity of a physical system to perform work. However, it's important to keep in mind that just because energy exists, it doesn't means it's necessarily available to do work.
- Energy refers to a condition or state of a sysyem or object.
- Energy can be store, can be transfered, can change the form
- The total amount of energy is conserved
- Energy is a scalar quantity

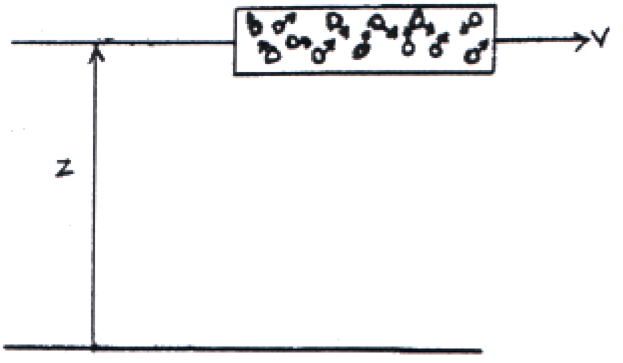
Forms of Energy: Energy can be in different forms:

- **Thermal energy (heat):** Heat or thermal energy is energy from the movement of atoms or molecules. It may be considered as energy relating to temperature.
- **Kinetic energy:** Kinetic energy is energy of motion.
- **Potential energy:** This is energy due to an object's position. For example, a ball sitting on a table has potential energy with respect to the floor because gravity acts upon it.
- **Mechanical energy:** Mechanical energy is the sum of the kinetic and potential energy of a body.
- **Electric energy:** This is energy from the movement of charged particles, such as protons, electrons, or ions.
- **Magnetic Energy** - This form of energy results from a magnetic field.
- **Chemical energy:** Associated with atomic bond in a molecule.
- **Nuclear energy:** Associated with strong bonds within nucleus of atom itself.

Macroscopic forms:

The total energy of a system consists of macroscopic and microscopic forms of energy.

Energy that a system possesses as whole with respect to some outside reference frame, such as **kinetic and potential** energies.



Kinetic energy, KE: Energy that a system possesses as a result of its motion relative to some reference frame.

$$KE = m\frac{V^2}{2}$$

Change in the kinetic energy ΔKE, of a body can be expressed as

$$\Delta KE = KE_2 - KE_1 = \frac{1}{2}m\left(V_2^{\,2} - V_1^{\,2}\right)$$

Potential energy, PE: Energy that a system possesses as a result of its elevation in a gravity field

$$PE = mgz$$

The change in gravitational potential energy is

$$\Delta PE = PE_2 - PE_1 = mg\left(z_2 - z_1\right)$$

Example: Consider a system having a mass of **1 kg** whose velocity increases from **15 m/s** to **30 m/s** while its elevation decreases by **10 m** at a location where **g = 9.7 m/s²**. Find the kinetic and potential energy, in kJ.

$$\Delta KE = \frac{1}{2} m \left(V_2^{\,2} - V_1^{\,2} \right)$$

$$= \frac{1}{2}(1kg)\left[\left(30\frac{m}{s} \right)^2 - \left(15\frac{m}{s} \right)^2 \right] \left[\frac{1N}{1kg \cdot m/s^2} \right] \left[\frac{1kJ}{10^3 N \cdot m} \right]$$

$$= 0.34 kJ$$

$$\Delta PE = mg\left(z_2 - z_1 \right)$$

$$= (1kg)\left(9.7\frac{m}{s^2} \right)(-10m)\left[\frac{1N}{1kg \cdot m/s^2} \right] \left[\frac{1kJ}{10^3 N \cdot m} \right]$$

$$= -0.10 kJ$$

Microscopic forms of energy

- Energies related to the molecular structure of a system and degree of the molecular activity.

- May be viewed as kinetic and potential energies of molecules
- Independent of outside reference frames

Internal Energy, U:

Sum of all microscopic forms of energy is called the **internal energy** of a system and it is denoted by **U**.

- Extensive property of the system

- Sum of all microscopic forms of energy. That is, all other energy changes are lumped together in the internal energy.

The change in internal energy in a process is

$$\Delta U = U_2 - U_1$$

The specific internal energy is symbolized by **u** or $\bar{u}$, respectively, depending on whether it is expressed on a unit mass or per mole basis.

<u>Sensible energy</u>
- Associate with kinetic energy of molecules
- Increase with increasing temperature

<u>Latent energy</u>
- Associate with bonds between molecules
- Related to phase of system

<u>Chemical energy</u>
Associate with strong bonds within nucleus of atom itself

Unit of Energy

Work = force x distance = N m

As seen unit of work in SI system is **Nm**. This called **Joule (J).** For convenience in this book **kilojoule** (**kJ)** is used as the energy unit.

In English Engineering unit system:

Work = lbfxft = Btu

Total Energy, E:
Total energy includes kinetic energy, gravitational potential energy, and other forms of energy. **All other energy changes are lumped together in the internal energy.**

$$E = U + KE + PE = U + \frac{mV^2}{2} + mgz \qquad \text{(kJ)}$$

Specific total energy, e:

$$e = \frac{E}{m} = \frac{U}{m} + \frac{KE}{m} + \frac{PE}{m} = u + \frac{V^2}{2} + gz \qquad \text{kJ/kg}$$

The change in the total energy of a system is:

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Where

$$\Delta U = U_2 - U_1$$

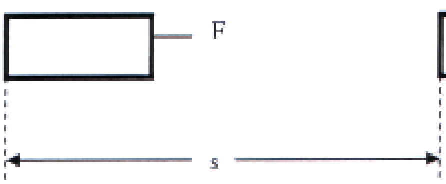
$$\Delta KE = KE_2 - KE_1 = \frac{m}{2}\left(V_2^{\,2} - V_1^{\,2}\right) \qquad \Delta PE = PE_2 - PE_1 = mg\left(z_2 - z_1\right)$$

For stationary closed system;

$$\Delta KE = 0 \qquad \Delta PE = 0$$

$$\Delta E = \Delta U$$

Work: Recall from physics that mechanical work related to a force acting through a distance



Work done by force **F** as it acts on the body along the distance **s** is $$W = \int_1^2 F ds$$

If **F** is constant, W=Fs (kJ)

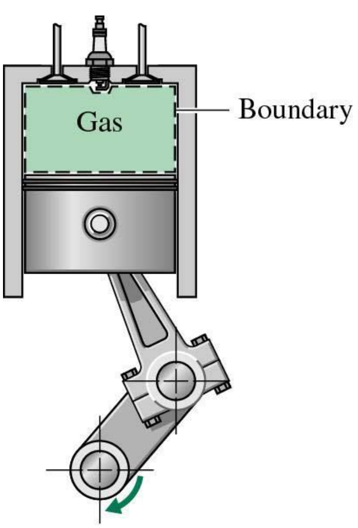
Forms of mechanical work in thermodynamics systems:

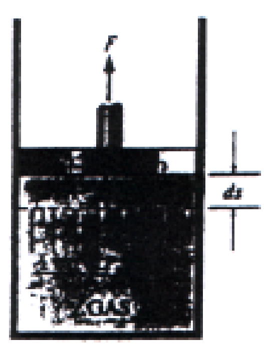
- Moving boundary work
- Shaft work
- Spring work
- Other mechanical forms of work (work done on elastic solid bar, work associated with the stretching of a liquid film, work done to raise or to accelerate a body)

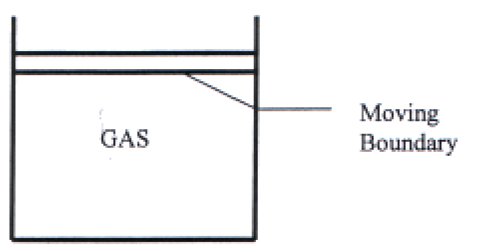
<u>Moving Boundary Work:</u>

This is the work done by the force acting on a moving surface.

- Expansion or compression of a gas in a piston-cylinder device
- Primary form of work involved in automobile engines





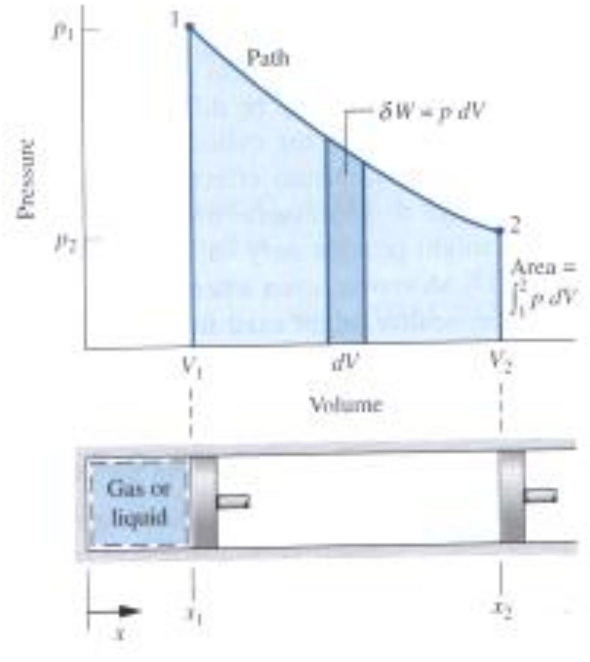


If piston is allowed to move a distance **ds** in a quasi-equilibrium manner, the differential work done during this process is

$$\delta W_b = F ds = pA ds = p dV$$

Moving boundary work and process path on a p-V diagram:

Consider the expansion of a gas in a cylinder-piston system. Assuming it is a quasi-equilibrium expansion process, on a p-V diagram process can be illustrated as follows:



Expansion work done by the gas on the piston from state 1 to 2 can be calculated as

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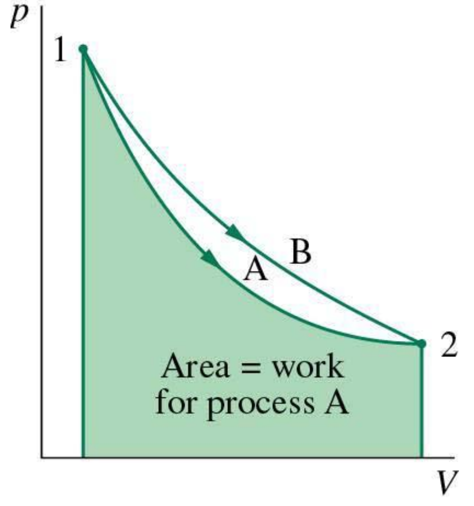
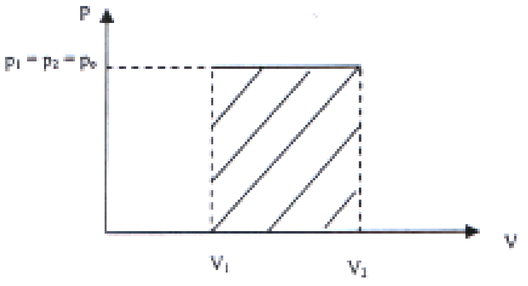
Note: Area under process curve on a p-V diagram is equal, in magnitude, to the work done.



In general as piston moves from state **1 to 2**, relation between pressure and volume could be different. That means **P-V curve** may follow different paths from state **1** and **2**. Hence, even though processes take place between the same states, area under the curves will be different. This yields different values for the work. This result reveals that

1) Work is path dependent (work is a path function).
2) Work is not a property.

Boundary work for a constant-pressure process:



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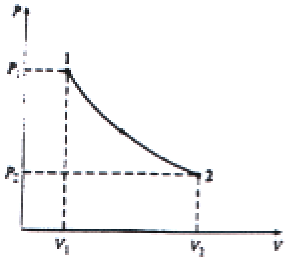
Boundary work for an isothermal process of an ideal gas:



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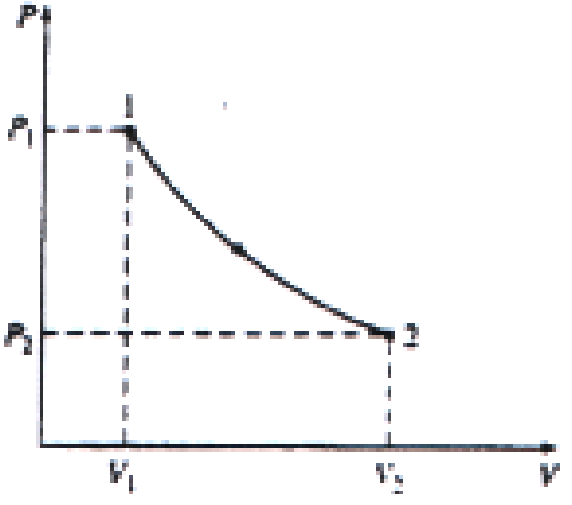
Boundary work for a polytropic process pV^n=constant:



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Example:

A gas in a piston cylinder assembly undergoes an expansion process for which the relationship between pressure and the volume is given by

$$pV^n = \text{constant}$$

The initial pressure is 3 bar, the initial volume is 0.1 m^3, and the final volume is 0.2 m^3. Determine the work for the process in kJ, if

(a) $n = 1.5$,

(b) $n=1.0$, and

(c) $n=0$.

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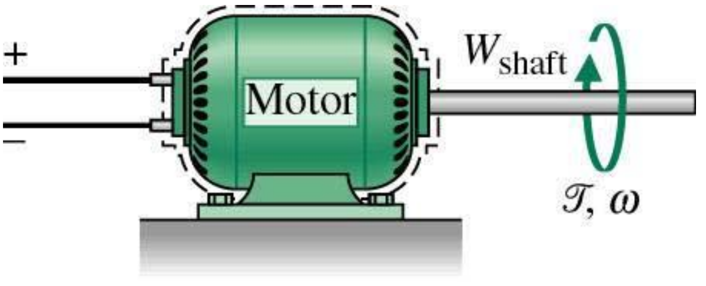
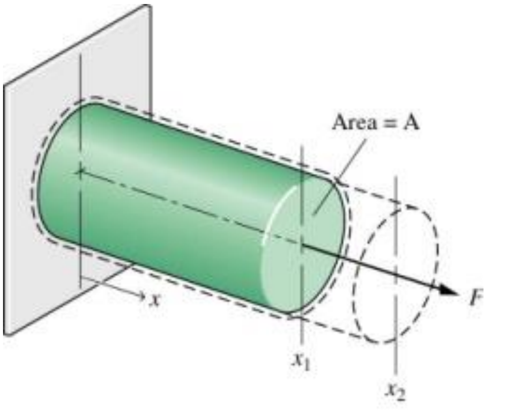
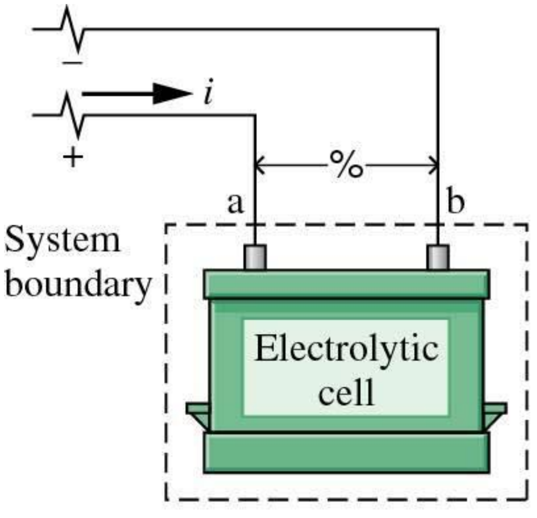
Other examples of work



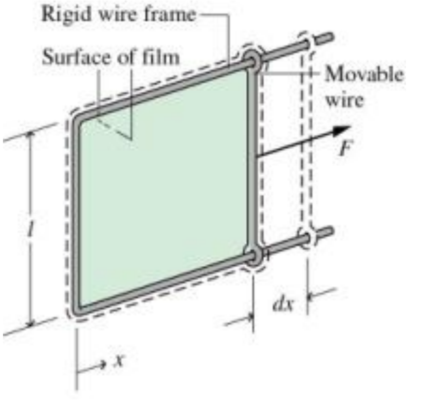
Shaft work (Power transmited by a shaft).



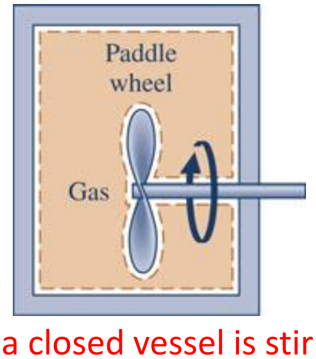
Elongation of a solid bar.



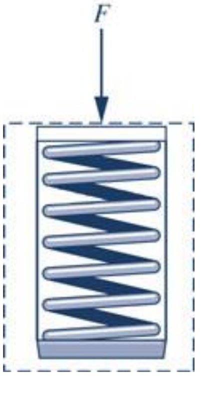
►When a battery is charged electrically, energy is transferred to the battery contents by work.



Stretching of a liquid film



hen a gas in a closed vessel is stirred, gy is transferred to the gas by work.



When a spring is compressed, energy is transferred to the spring by work

Power

Many thermodynamic analysis are concerned with the **time rate** at which energy transfer (energy trenfer in unit time) occurs. The rate of energy transfer by work is called power and denoted by **W**.

Rate of the work (power) done by a force **F** can expressed as

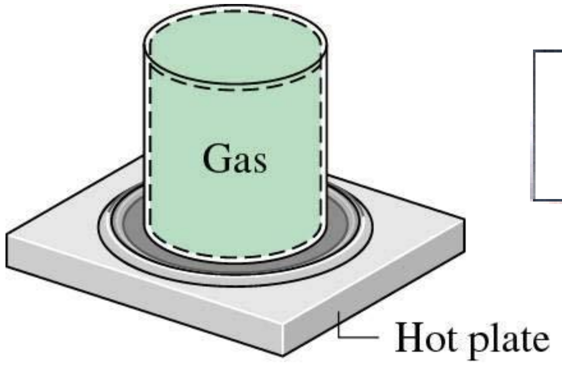
Power = Work/Time

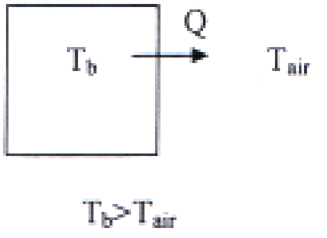
Complete in class

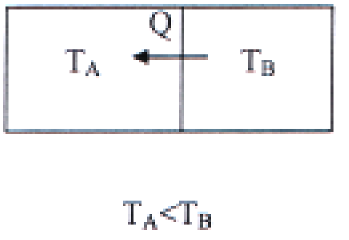
Energy Transfer By Heat:

A system may interact with the surrounding by work and heat transfer. Hence the heat transfer is another way for energy transfer between a system and the surrounding.

When temperature of a system is different from the temperature of surrounding, heat transfer between the system and surrounding takes place according to the zeroth law of thermodynamics.







- Heat is always transferred from the higher temperature body to lower temperature one.
- No heat transfer if two bodies have the same temperature.
- The value of heat transfers depends on the details of the process, not just the end states. Hence **heat is not a property**.

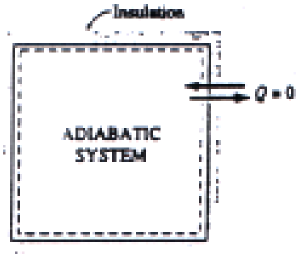
- Heat has energy units, **kJ or Btu**

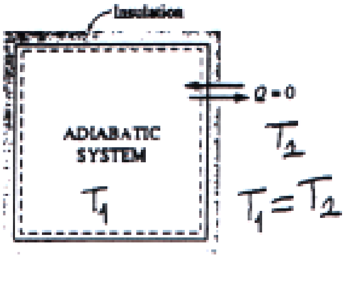
Adiabatic Process

Adiabatic process is a process during which there is no heat transfer between the system and the surrounding.

There are two easy ways that a process can be made adiabatic

1) The system is well insulated; the amount of heat that can pass the system boundary is negligible
2) Both the system and surroundings are at the same temperature (no driving force)





Heat Transfer Rate

Heat transfer *per unit mass* of a system is denoted *q* and is determined from:

Sometimes it is desirable to know the *rate of heat transfer* (the amount of heat transferred per unit time)

The amount of energy transfer by heat for a process from state 1 to state 2 is

Q_{12} or Q (kJ)

$$Q = \int_1^2 \delta Q$$

where the limits mean "from state 1 to state 2" and do not refer to the values of heat at those states.

Heat transfer per unit mass:

$$q = \frac{Q}{m} \qquad \text{(kJ/kg)}$$

The amount of energy transfer by heat during a period of time can be found by integrating from time $\mathbf{t_1}$ to time $\mathbf{t_2}$

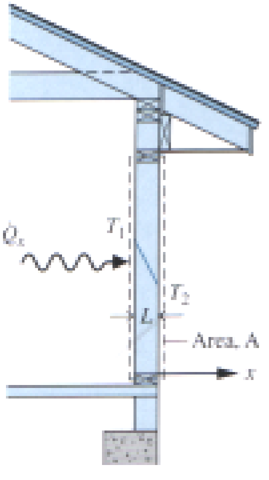
$$Q = \int_{t_1}^{t_2} \dot{Q}\, dt \qquad \text{(kJ)}$$

Heat transfer modes:

Heat is transferred by three mechanism:

1) **Conduction heat transfer:** This is the heat transfer within the material due to the molecular vibrations (solid/fluid/gas in rest)
2) **Convection heat transfer:** This is the heat transfer between a moving fluid past a solid surface that is at a different temperature than fluid.
3) **Radiation heat transfer**: This is the heat transfer in the form of electromagnetic waves.

Conduction Heat Transfer:



Conduction is the transfer of energy from more energetic particles of a substance to less energetic adjacent particles due to interactions between them.

The time rate of energy transfer by conduction is quantified by *Fourier's law*.

By Fourier's law, the rate of heat transfer across any plane normal to the x-direction, proportional to the wall area, A, and temperature gradient in the x direction, dT/dx. This relation can be expressed as

$$\dot{Q}_x = -\kappa A \frac{dT}{dx}$$

Where proportionality constant κ is a property called the thermal conductivity. The **minus sign** is a consequence of energy transfer in the direction of decreasing temperature.

In this case, temperature varies linearly with x, and thus

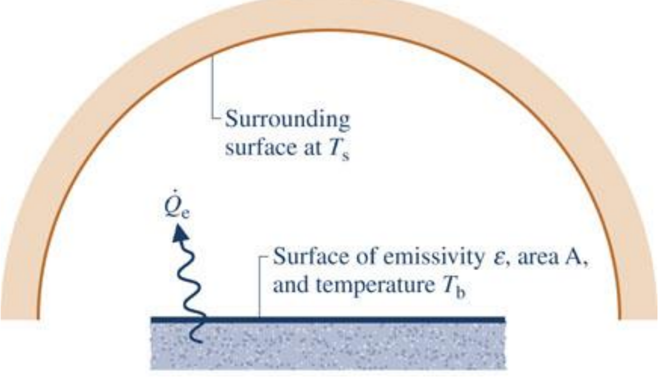
$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} (< 0) \qquad \dot{Q}_x = -\kappa A \left[\frac{T_2 - T_1}{L}\right]$$

Radiation

Thermal radiation is energy transported by electromagnetic waves (or photons). Unlike conduction, thermal radiation requires no intervening medium and can take place in a vacuum.

The time rate of energy transfer by radiation is quantified by expressions developed from the *Stefan-Boltzman law*.

An application involving net radiation exchange between a surface at temperature T_b and a much larger surface at T_s (< T_b) is shown at right.



$$\dot{Q}_e = \varepsilon\sigma A[T_b^4 - T_s^4]$$

where
A is the **area** of the smaller surface,
e is a property of the surface called its **emissivity**,
σ is the **Stefan-Boltzman constant**.

Convection

Convection is energy transfer between a solid surface and an adjacent gas or liquid by the combined effects of conduction and bulk flow within the gas or liquid.

The rate of energy transfer by convection is quantified by *Newton's law of cooling*.

$$\dot{Q}_c = hA(T_b - T_f)$$

A : surface area
h : heat transfer coefficient
h is not a thermodynamic property.